FLIGHTS of DISCOVERY

75 Years of Flight Research at the NASA Armstrong Flight Research Center

75
ARMSTRONG FLIGHT RESEARCH CENTER
1946-2021

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Frontispiece

On October 4, 1957 the Society of Experimental Test Pilots gathered at the Beverly Hilton, in Los Angeles, CA for the group's first annual awards banquet. The attendees included such well-known research and test pilots as Joseph A. *"Joe"* Walker, A. Scott Crossfield, William B. *"Bill"* Bridgeman, Anthony *"Tony"* LeVier, Lt. Gen. James *"Jimmy"* Doolittle, and Maj. Gen. Albert Boyd.

Among the younger group of pilots at the banquet was one who had already flown several project aircraft at the NACA High-Speed Flight Station, including the B-29 launch aircraft, the B-47, F-100, F-51, and R4D. He'd made his first rocket plane flight in the X-1B not two months earlier. Better than anyone else at the gathering, Neil A. Armstrong symbolized how much would change with the launch of Sputnik that night.

It had been ten years almost to the day since the first supersonic flight and this night marked another great divide: between what came before Sputnik and what came after. Armstrong was part of the transformation the NACA brought about with the early X-planes and he became part of what it led to. The NACA set up the new agency – NASA – for the next step: space. The reformulated agency was at once properly suited for the task handed to it and the only entity suited for that task. Indeed, NASA was prepared precisely because of what it went through in the previous decade, and in large measure because of the work done by the Armstrong Flight Research Center at Edwards Air Force Base.

This is our story.

David D. McBride

Center Director

NASA Armstrong Flight Research Center

Neil A. Armstrong. ©Photo by Ted Huetter

Contributions

Continuing Purdue University's long-standing capability of contributing to the history, science, technology and personnel of the United States' space and aeronautics programs, a group of Purdue students has taken their place in this endeavor by the compilation, formatting, and electronic publication of historical materials to produce a first-of-its-kind interactive eBook to celebrate the 75th anniversary of Armstrong Flight Research Center. The National Aeronautics and Space Administration's (NASA) premiere aeronautics and flight test facility, Armstrong Flight Research Center, located on Edwards Air Force Base in California was the location of the second job of its future namesake and fellow Purdue alumnus, Neil A. Armstrong, after graduation.

Armstrong enrolled at Purdue University in 1947 on a Navy scholarship and pursued a degree in aeronautical engineering. He was called to active duty in the Navy in 1949 and served in the Korean War. He returned to Purdue and completed his degree in 1955.

Armstrong was a true Boilermaker. Many do not know that the first man to step on the Moon wrote and directed musicals and played the baritone in the Purdue All-American Marching Band. He was a member of the Purdue Radio-Controlled Aircraft Club and The Aero Flying Club flying full-sized aircraft. The Neil Armstrong Hall of Engineering houses the School of Aeronautics and Astronautics, the School of Materials Engineering, and the School of Engineering Education and was dedicated by him in 2008. The Purdue Archives and Special Collections is also the home of The Neil A. Armstrong Papers that document the military, aeronautics, astronautics, teaching and corporate business career of Neil A. Armstrong.

The Purdue Polytechnic Institute is grateful for the opportunity to produce the online portion of this product in cooperation with NASA. Computer Graphics Technology seniors, Christopher Hollopeter, Annelise Furtner, Kelly Chen and Dillan Baesler contributed hundreds of hours in their capstone course to generate a product worthy of the proud tradition of contributing to the mission of NASA.

Boiler Up!

Daniel K. Ward II
Lecturer/Project Mentor
Purdue University

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Acknowledgements

No book or project of any scope or size can be produced without the combined efforts of a number of people. This fact is even more true for a book such as this one, which is, essentially, the collective story of all the people who worked for or with the NASA Dryden Flight Research Center over a period of 60 years. Without the talent, effort, blood, sweat, and tears they contributed to the center over those many years, there would have been no story to tell.

It also would have been impossible for me to tell that story without the cooperation and patience of the many Dryden employees, contractors, and research partners – far too many to list – who willingly shared their time, thoughts, memories, and files with me in the course of my research for both this book and the original *"Flights of Discovery"* illustrated history I wrote 10 years ago. The thoughts and perspectives of the engineers, researchers, and managers of both retired and current center professionals were invaluable in helping me to understand not only individual research projects, but also the essential character of Dryden, as well as the shifting winds of change that have affected the center's work over the years.

In addition, I would like to thank Bob Meyer, Dill Hunley, and Kevin Petersen, as well as my good friend Bruce Williams, for reviewing the manuscript for me and offering many helpful comments and thoughts; the incredibly talented Dryden photographers, without whom there would be no photos to illustrate this story; and the graphic design department that was tasked with turning these words and photos into a seamless, beautiful whole.

In short, this book is a reflection of the Dryden Flight Research Center itself—the combined effort of many talented people who created a whole that is far, far greater than the sum of its parts. And if I am in debt to the individuals at Dryden who made this book possible, it is only a small echo of the debt owed by the nation to this very unique group of people—dedicated professionals who have spent 60 years turning dreams into reality and helping us to fly faster, higher, more safely, and more efficiently as we reach for the both the skies and the stars.

Lane Wallace, 2006

Any book is the result of the combined efforts of many people. This is even truer for a book that is a collective story of all the people who worked for or with NASA's Neil A. Armstrong Flight Research Center over a period of seventy-five years. Without their talent, effort, blood, sweat, and tears there would be no story of the Center to tell.

It also would have been impossible to bring this story to you without the cooperation and patience of the many Armstrong employees, contractors, and research partners – far too many to list – who willingly shared their time, thoughts, memories, and files to make this book a reality. Particular recognition goes to Armstrong's peerless photographers, one of whom, Carla Thomas, selected the images for this edition. Steve Lighthill laid out the new edition of this book—as he did the 2006 edition, and Jay Levine's Armstrong X-press was invaluable as background to the author. And to David McBride, Armstrong Director, goes credit for insisting this project be renewed for the Center's seventy-fifth anniversary.

Dr. Christian Gelzer, 2020

Foreword

Seventy-five years ago Armstrong's first personnel arrived in the High Desert of California from the National Advisory Committee for Aeronautics' (NACA) Langley Memorial Aeronautical Laboratory, in Virginia. These engineers, mechanics, computers, and pilots came to the sparse desert as part of a team with one goal: to see if an airplane—the X-1—could be flown successfully faster than the speed of sound. They achieved their goal by 1947, but by then they'd had two epiphanies. First, everything they knew about high speed flight was irrelevant because they were exploring a realm of flight never visited before. Ahead lay countless questions and a nation needed answers. Second, and as a result of the first, they would not be going back to Virginia anytime soon: new vistas and problems of flight lay ahead. What began as a temporary flight research station became a permanent flight research Center as a result.

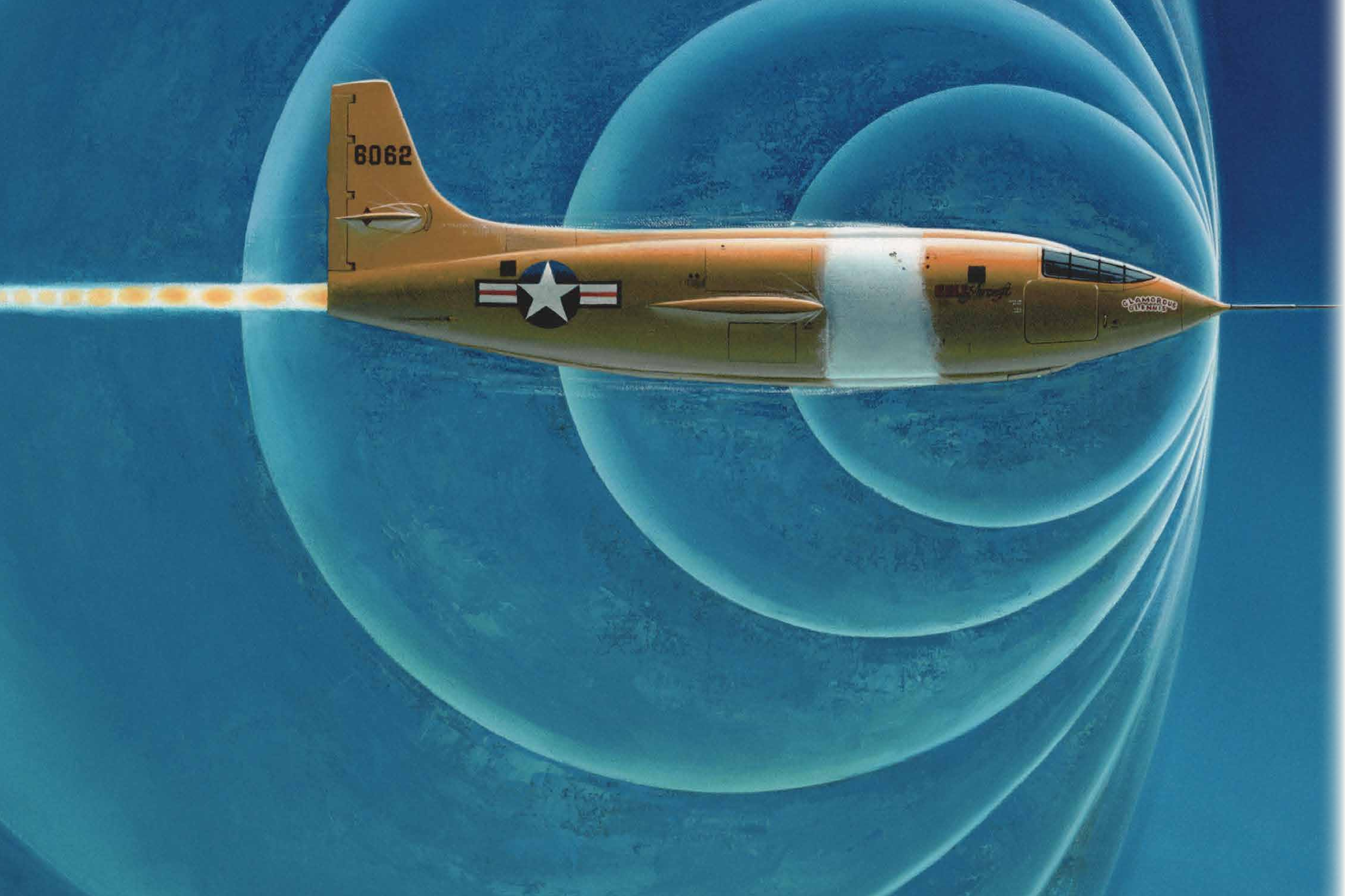
The NACA was chartered in 1915 to explore issues of flight, to ask questions others could not, and to re-establish the nation's leadership in aeronautics. Over the past seventy-five years those in the high desert of Southern California played pivotal roles in some of the most incredible—and important—developments in aviation and spaceflight. Much of what the world is now familiar with in spaceflight and aeronautics—and a great deal it is not yet aware of—had its roots at NASA's Neil A. Armstrong Flight Research Center.

The Center and its researchers are perhaps most frequently recognized for their roles in the advances of high-speed flight, and not just because of the success of the X-1 in surpassing the speed of sound. Armstrong was the home of the X-15, the fastest manned aircraft in history until the space shuttle. But Armstrong has been much more than high-speed research. It was the birthplace or validation point of in-flight swing wing aircraft, analog and digital flight and engine control systems, remotely piloted research aircraft, more efficient wings, winglets, controlled flight through engine thrust alone, thrust vectoring, and wings that swivel to an oblique angle in flight, for instance. Armstrong demonstrated a vehicle to train astronauts for a landing on the moon, and introduced the world to wingless flight. Armstrong sent aircraft into space and returned them to land on Rogers Dry Lake bed years before the shuttle ever left the drawing board—indeed, the Center was the first to put the same person into space twice, and did so in barely a months' time. The Center was home to the first shuttle landings, as well as the highest-flying aircraft ever—a solar-powered flying wing. Work conducted at Armstrong has improved the safety and efficiency of air travel, and has shown the world our own planet and the natural environment in which we live in ways never seen before. The Center's seventy-five years of aerospace technical expertise in one-of-a-kind flight projects continues to be invaluable to NASA and industry partners in design, research, and validation. Armstrong has the distinction of decades of experience in unmanned aircraft systems and remains on the cutting edge of aeronautics and spaceflight.

In the last several decades the Center has added much to its portfolio. Unmanned Aerial Systems and Advanced Air Mobility promise quick individual transportation by air and the Center has worked with the FAA and industry to incorporate UAS operations in the National Air Space. The Center paved the way for the adoption of Fiber Optic Strain Sensing on aircraft, which NASA is now examining for use on rockets, among other applications. Electric propulsion aircraft are an alternative to fossil fuel combustion for flight. Armstrong is responsible for integration and flight testing the aircraft. And Armstrong will fly the X-59, a platform to validate technologies to reduce the impact of the sonic boom of supersonic flight, leading to commercial supersonic flight over land. Armstrong operates SOFIA, a stratospheric infrared telescope carried on a Boeing 747SP in a joint NASA/DLR (German aeronautics research agency) program. The Active Compliant Trailed Edge (ACTE) is a morphing flap which the Center tested on one of its Gulfstream GIII. And Armstrong has been flying a series of scaled gliders sporting a new spanload: the result is an aircraft that does not need a rudder or its equivalent to make coordinated turns. Its efficiency potential is stunning. And in a project with the Department of Defense, Armstrong helped perfect the Automatic Ground Collision Avoidance System (Auto-GCAS), first carried on F-16s and now available to general aviation in a modified form. For this the agency shared in the 2018 Collier Trophy, one of 19 the agency has won or been a supporting contributor to since 1929. These are just a few examples of the Center's work. Those who first came to the High Desert and what is now Edwards AFB in 1946 would barely know the place, yet they would recognize the imagination, initiative, drive and spirit of the Center today.

Unlike many NASA Centers, Armstrong has always been hard to spot, located on an active Air Force base, far removed from population centers as it is. Much of what Armstrong has done escapes the public's attention. Despite this, Armstrong's research has a direct impact on all our daily lives. This book is a window onto the contributions we at NASA's Neil A. Armstrong Flight Research Center have made to aeronautics and spaceflight, and to the nation in general.

Dr. Christian Gelzer - Historian - Logical Innovations, Inc - NASA Neil A. Armstrong Flight Research Center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GLAMOROUS GLENNIS

Chapter 1

Origins

Compression and
penetration
by Nixon Galloway

Origins

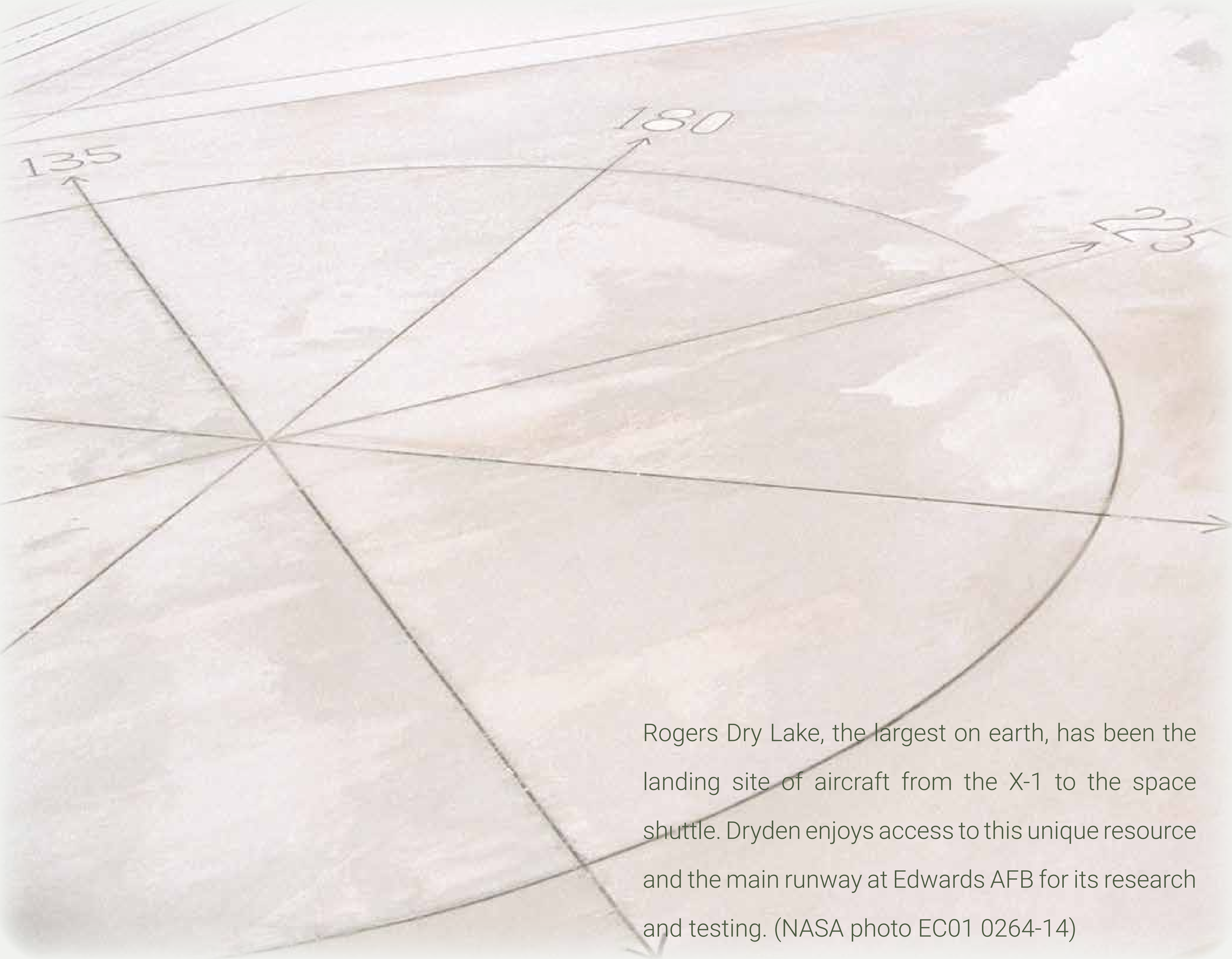
Somewhere, right now, several thousand airliners and business jets are streaking through the skies above us, bringing people and goods to destinations all over the world in a mode of transportation that is not only highly efficient, but has developed a safety record many times better than that of automobiles. Somewhere else, supersonic fighter aircraft are patrolling the skies to protect America's borders and helping to keep the peace in numerous troubled parts of the world. Somewhere else, scientists are using the data brought back from aircraft sensors to broaden their understanding of our atmosphere, climate, and planet so we can improve our planning for natural events and preserve the critical natural resources we need to survive. Turning slowly in the heavens even farther above us, the Hubble Space Telescope brings back images from distant galaxies, while astronauts work to construct a research station and home in space.

None of these advances, conveniences, and accomplishments – resources and capabilities we take for granted in our daily lives – appeared overnight. The countless improvements in safety, science, and quality of life that aircraft and spacecraft have made possible came from the blood, sweat, and tears of thousands of individuals over the course of more than 100 years. They came from the imaginations of inventors, from the design and drafting tables of engineers, from tedious and exacting experiments in research laboratories and wind tunnels...and from repeated exploration and testing of concepts and technology in flight.

Even before the Wright brothers took their famous Flyer into the skies above the dunes of Kitty Hawk, Wilbur Wright realized the critical importance of testing concepts not only with models or in the small wind tunnel the brothers invented, but in the sky itself. "*If you are looking for perfect safety,*" he argued in 1901, *"you will do well to sit on a fence and watch the birds. But if you really wish to learn, you must mount a machine and become acquainted with its tricks by actual trial."*[1]

This has been true ever since. No matter how simple or complex the aerospace concept or design is, and no matter how advanced ground research facilities have become, there remains only one way to know for certain how a design or concept will operate in a real-world environment, and that is for someone to take it there. As NASA Administrator James E. Webb argued before Congress in 1967,

> *Flight testing of new concepts, designs, and systems is fundamental to aeronautics. Laboratory data alone, and theories based on these data, cannot give all the answers... Each time a new aircraft flies, a "moment of truth" arrives for the designer as he discovers whether a group of individually satisfactory elements add together to make a satisfactory whole, or whether their unexpected interactions result in a major deficiency. Flight research plays the essential role in assuring that all the elements of an aircraft can be integrated into a satisfactory system.*[2]



Rogers Dry Lake, the largest on earth, has been the landing site of aircraft from the X-1 to the space shuttle. Dryden enjoys access to this unique resource and the main runway at Edwards AFB for its research and testing. (NASA photo EC01 0264-14)

Flight Research

And yet, advances in aeronautics and aerospace technology derive from more than simple testing of new aircraft and systems to ensure that components work together well. They also stem from the efforts of researchers, technicians, pilots, and support personnel who, like explorers for centuries before them, have devoted themselves to the larger task of expanding our understanding of aeronautics, space, and flight itself. This broader, questioning endeavor is known as flight research – a unique and challenging type of exploration that the professionals at NASA's Dryden Flight Research Center have pursued with single-minded dedication for more than seven decades.

Flight test and flight research are very closely related fields and, at least to the casual observer, the two can be almost indistinguishable. Both flight test and flight research involve the design, manufacture, and flight testing of components, engines, controls, and/or actual vehicles. Both employ highly skilled pilots who fly new and experimental aircraft configurations to precise test points. In both cases, data from those maneuvers is collected with various types of instrumentation and either recorded or sent back to the ground, where it is processed and analyzed by engineers, technicians, and specialists.

The difference between flight test and flight research is a subtle one. Research tends to be more open ended, while testing has specific and expected results. The first often leads to more questions; the second tends to result in answers. This is of course not a fast rule, and Dryden has in many ways always done both, simply out of necessity.

In flight test, the objective is often to compare an aircraft's performance or a component's functionality against set specifications it is supposed to meet. The idea is not to explore new realms of aeronautical knowledge, but to make sure that a new aircraft design, configuration, or component performs in an acceptable or expected manner. Unless the anomaly is better-than-predicted performance, unexpected results in a flight test program indicate problems that need fixing. The information gained through flight test is also directed toward a specific customer with regard to a specific product.

Flight research, on the other hand, gathers information that can be used by a much broader audience in a wide variety of applications. The objective is not simply to determine whether an airplane performs in a certain way, but to understand why it does and to explore various factors affecting the performance. In the field of flight research, discoveries are not problems to be fixed but doors opening into new realms of possibility. They are marked far less often by a triumphant shout of, *"Eureka!"* than by a perplexed murmur of, *"That's odd..."* And yet, the same anomaly that might indicate failure in a flight test program can sometimes mark a breakthrough in the field of flight research. Those moments in which results diverge from expectation can give researchers valuable glimpses into a realm beyond what is known, raise new questions, and lead to entirely new lines of research.

This in-flight NACA High-Speed Flight Station photograph of the X-3 Stiletto illustrates the aircraft's long slender fuselage and the small wings. (NASA photo E-17348)

U. S. AIR FORCE
X-3

Flight Discovery

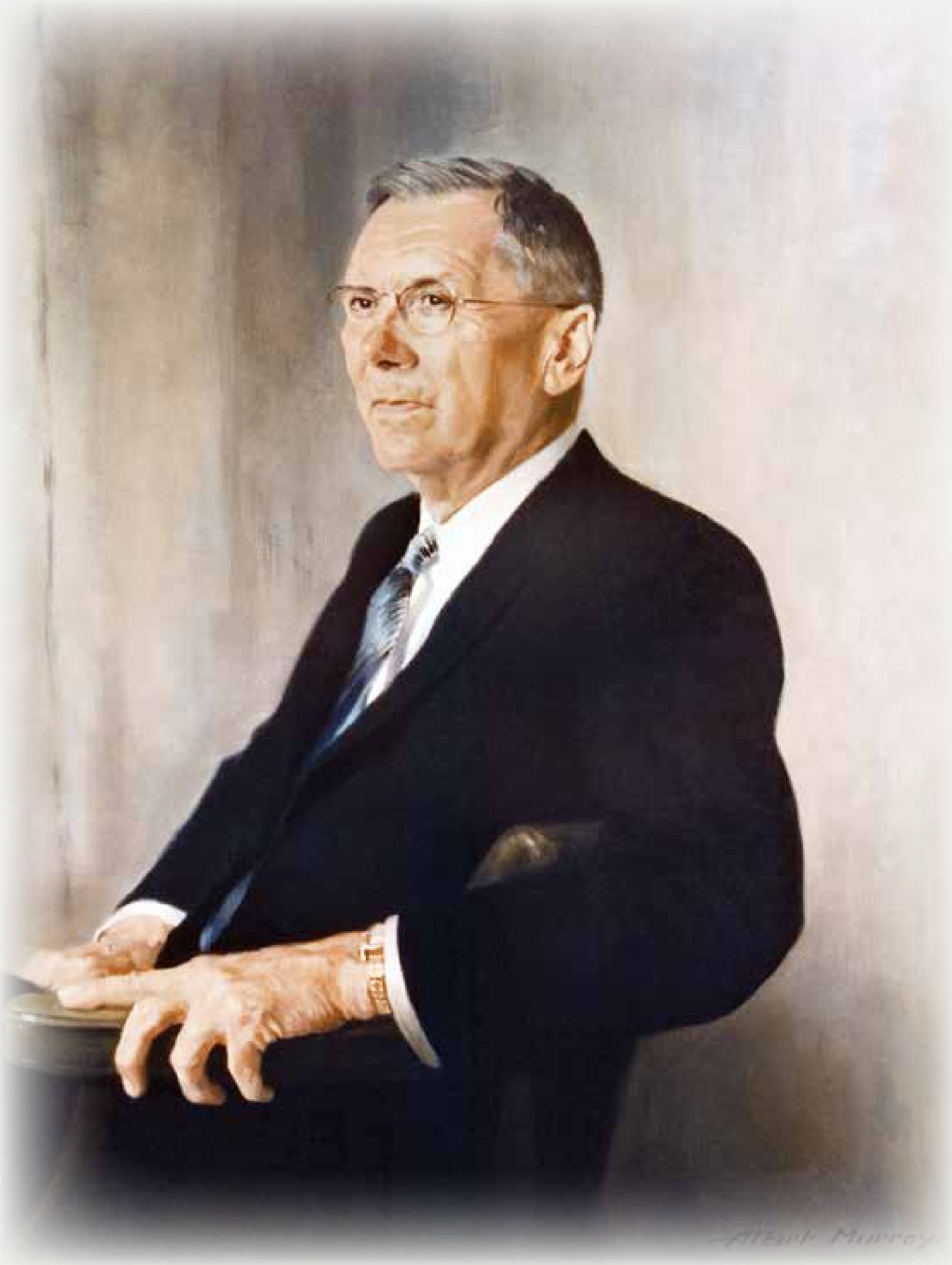
Discovery happens in all types of research settings, of course. But the potential for discovery is particularly great in flight research, because it is an arena where so many variables and unknowns come together. It was, for example, through the unexpectedly poor performance of their 1901 glider at Kitty Hawk that the Wright brothers discovered that some of the basic, accepted tenets of aeronautics of the time were seriously flawed. That discovery led the Wrights to conduct the first scientific wind tunnel experiments in airfoil aerodynamics – which, in turn, led to their successful 1903 Wright Flyer. And while ground research facilities and predictive tools have improved by many orders of magnitude in the century that followed, many of the projects at the Dryden Flight Research Center have produced at least one unexpected discovery.

Yet the importance of flight research goes even beyond its ability to facilitate discovery and expand basic understanding. Flight offers a valuable way to verify ground predictions and computer codes, giving engineers more confidence in using those tools to design new vehicles and systems. Taking a concept or piece of technology to flight also helps advance its technological readiness, because in order to test something in a flyable aircraft researchers must resolve many questions and problems, including issues of safety, size, robustness, power requirements, redundancy, and integration with other elements or systems.

Hugh L. Dryden, for whom the Dryden Flight Research Center is named, once said that flight research separated *"the real from the imagined."* There remains no better way to settle questions about an aeronautical concept or technology than by flying it. As a former vice president of engineering at The Boeing Commercial Airplane Company argued,

> *Laboratory development has great appeal and usually gets substantial government support. However...the attainment of credibility is [also] an important national issue. It is during this second phase that a technical concept achieves a state of readiness, validation and credibility such that private industry and financing can assume the attendant risks.*[3]

The aerospace industry has its own research and development budgets that are far larger today than they were in the 1920s and 1930s. But the focus of a company beholden to stockholders is inherently different from that of a nonprofit or government research institution. Private companies can and will pursue research in areas where direct links to marketable products can be identified. But in the context of a continually fluctuating national economy it remains difficult for the aerospace industry to invest the significant time, funds, and effort necessary to pursue basic research or pursue possibilities very far into the future, or unrelated to a specific product or commercially viable design.


Painting of Hugh L. Dryden (1898-1965), for whom the Dryden Flight Research Center was named in March of 1976. Painting done by Albert Murray of New York. (NASA photo ECN 5011)

Flight research for the sake of expanding knowledge or creating a national capability for as-yet-unidentified future needs is expensive, as well as time and labor-intensive. Its rewards are often uncertain, may pay off only somewhere far down the road, or will yield a return only if a future need or mission arises requiring that particular advance in knowledge or capability. And yet without forward-looking investment in this effort, the nation will not have the understanding, technology, and ability to capitalize on opportunities to improve aircraft or spacecraft, or to meet future needs in defense, safety, homeland security, commercial transportation, and exploration.

The Dryden Flight Research Center

It was for this reason that the U.S. Congress, in 1915, set up the National Advisory Committee for Aeronautics (NACA), NASA's predecessor agency. The NACA was established specifically *"to supervise and direct the scientific study of the problems of flight with a view to their practical solution."*[4] By 1915 World War I was underway in Europe and aircraft were playing an increasingly important role in the conflict. It had become clear that, while the U.S. might have been the first country to achieve powered, controllable flight of an airplane, government-funded research efforts in Germany, France, and England had allowed European aircraft manufacturers to far outdistance American capabilities.

In the years since, research conducted by the NACA and NASA has played a critical role in building and maintaining a strong and safe air commerce system, aiding national defense, exploring space, and advancing U.S. aerospace technology in an increasingly competitive global market. That research has taken many forms, but flight research has always been a significant and invaluable piece of the mix.

The facilities of the NACA installation (later known as the Dryden Flight Research Center) on August 24, 1954, including the new headquarters building and two hangars. In the background is Rogers Dry Lake, which provides a natural landing site for research aircraft. (NASA photo E-1361)

The Dryden Flight Research Center

From the founding of the NACA in 1915 until the end of World War II, the majority of the committee's flight research was conducted at the Langley Research Center in Hampton Roads, Virginia. But World War II, and the technology advances that occurred during the war years, created new requirements for flight research and for testing locations and facilities.

In 1933, Col. Henry *"Hap"* Arnold, who later became head of the Army Air Forces in World War II, went in search of a new bombing and gunnery range. He found what he was looking for in the vast stretches of the Mojave Desert, about 100 miles north of Los Angeles, California. The Mojave encompasses 25,000 square miles of barren wilderness marked with a smattering of spiny Joshua trees, sagebrush, and large, flat lakebeds that are dry for most of the year. It is a land of extremes, with blazing-hot summers, bone-chilling winters, and winds that sweep down from the Tehachapi Mountains, sending tumbleweeds careening across the arid landscape. But the very characteristics of the land that drove Arnold to describe it as *"not good for anything but rattlesnakes and horned toads"* made the Mojave Desert an ideal location not only for a bombing range, but also as a flight test facility for new aircraft designs emerging from the war effort.[5]

Until World War II, the Army conducted the majority of its aeronautical development and testing at Wright Field, near Dayton, Ohio. But it was next to impossible to conduct secret testing in the skies over the settled landscape of Ohio. Arnold's Muroc Army Airfield, on the edge of the 44-square-mile Rogers Dry Lake in the Mojave Desert, offered a far more suitable flight test site, and for several reasons.

First, Muroc was a remote location, where security on the ground and in the air could be assured. New turbojet designs could be flight tested there without catching the attention of residents, or putting them at risk in case of a mishap. Second, dry lakebeds offered unparalleled options for alternative landing sites, a growing necessity as the experimental aircraft being tested became faster and more powerful, requiring longer surfaces in order to land safely. Third, the desert weather was exceptional for flight test activities. The arid climate generated crystal-clear blue skies almost 360 days of the year, with visibilities often greater than 100 miles.

The Bell X-1 Rocket Plane

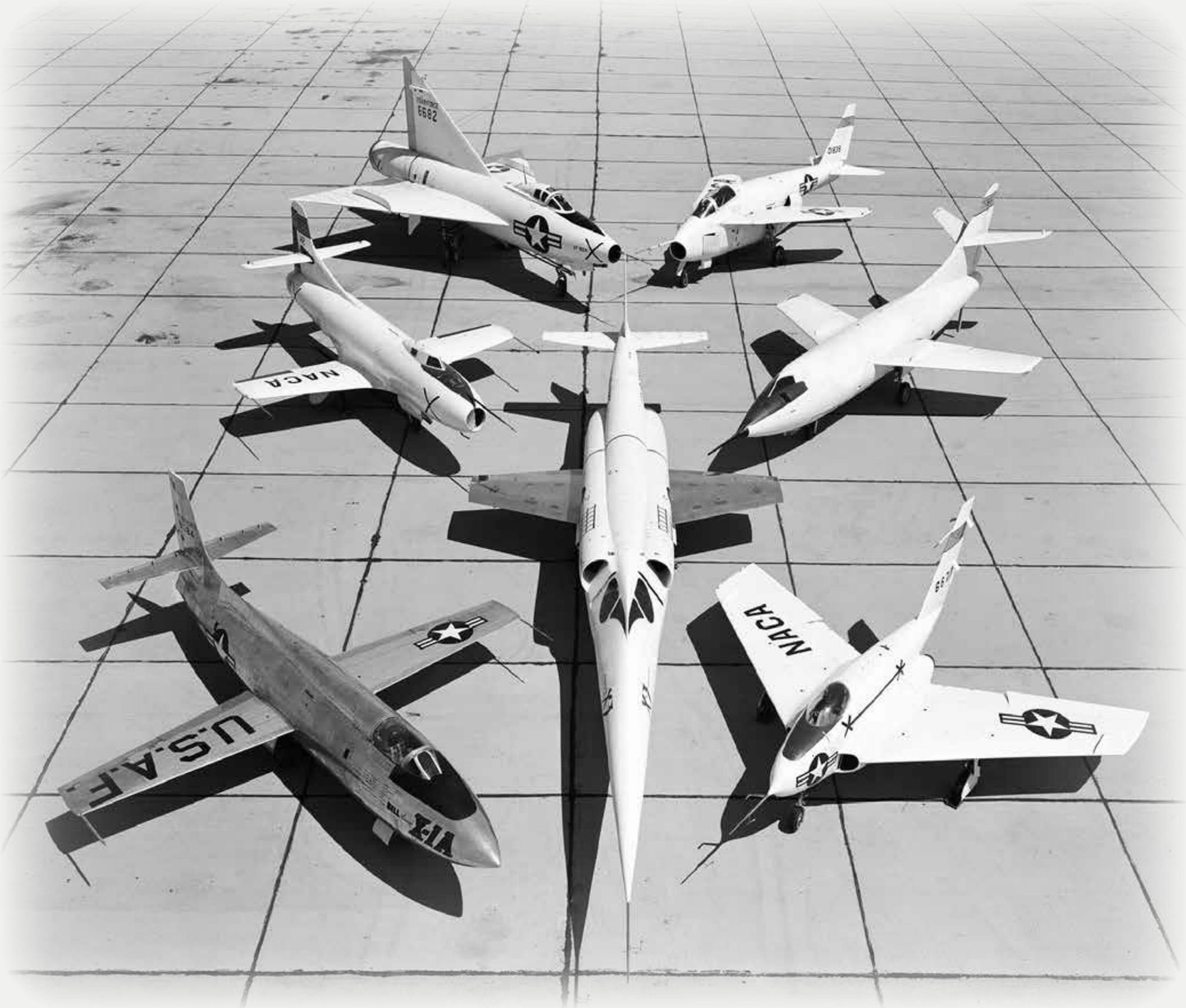
As early as 1942, the Army was testing the Bell XP-59A Airacomet – America's first jet airplane – in the skies over Muroc. But four years later, an even more secret project arrived at Muroc that would change both the base and the world of flight forever: the Bell X-1 rocket plane.

The X-1, originally designated the *"XS-1"* for *"Experimental Sonic,"* was a research aircraft designed to explore the seemingly impenetrable barrier to flight at and beyond the speed of sound. It was a joint effort between the NACA and the Army Air Forces, but it needed to operate off a longer and more secure runway than that at the NACA's Langley Research Center or at any East Coast facility, for that matter. So in September 1946, a contingent of 13 NACA engineers and technicians left Langley to set up what was envisioned as a temporary research base at the Muroc Army Airfield in the Mojave Desert.

A year later, the X-1 successfully *"broke"* the sound barrier. But the questions and possibilities related to flight in this new, high-speed realm were just beginning. New *"X-planes"* were coming down the pike, each one with new challenges, capabilities, and questions to be answered. In addition, the new supersonic jet fighters the military was putting into service were running into a variety of unexpected phenomena and problems. Clearly, there was a huge and pressing need for more research in this new realm of flight, and the research team and facilities at Muroc were proving to be a very valuable national asset. So although it wasn't initially planned that way, the temporary unit on the edge of Rogers Dry Lake slowly evolved into a permanent research base that would, in time, become the premier flight research facility in the world.

ONAL ADVISORY COMMITTE
FOR AERONAUTICS
FLIGHT STATION

In October 1958, workers at the High Speed Flight Station (HSFS, as NASA Dryden was then called) removed the NACA name and emblem from the front of the headquarters building to replace it with the NASA designation and symbol. The next year (1959), the HSFS became the NASA Flight Research Center in one of the institution's many name changes. (NASA photo E96 43403-4)



This 1954 photo shows many of the early research aircraft at what became the Dryden Flight Research Center. Clockwise from the lower left: the Bell X-1A, the Douglas D-558-1 Skystreak, the Convair XF-92A, the Bell X-5, the Douglas D-558-2 Skyrocket, the Northrop X-4, and, in the center of the photo, the Douglas X-3. (NASA photo E-2889)

Even before Capt. Charles *"Chuck"* Yeager flew the X-1 past the speed of sound, the NACA and the Army Air Forces had signed a joint agreement for work on a complete series of X-planes, from the X-1 to the X-5, and the Langley contingent was given an official designation as the NACA Muroc Flight Test Unit. By 1949, Muroc was renamed Edwards Air Force Base in memory of Capt. Glen W. Edwards, an Air Force test pilot killed the previous year in the crash of a YB-49 Flying Wing, and the Langley outpost was renamed the NACA High Speed Flight Research Station (HSFRS).

The NACA contingent at Edwards remained part of the Langley Research Center until 1954, when it was redesignated the NACA High Speed Flight Station (HSFS) and made an autonomous facility reporting directly to the NACA headquarters. That year, the station's employees, who now numbered 250, moved into new facilities halfway between the more secretive *"North Base"* section of Edwards and the larger *"South Base"* Air Force facilities. Those original NASA facilities have been expanded and updated since that time, but are still in use today.

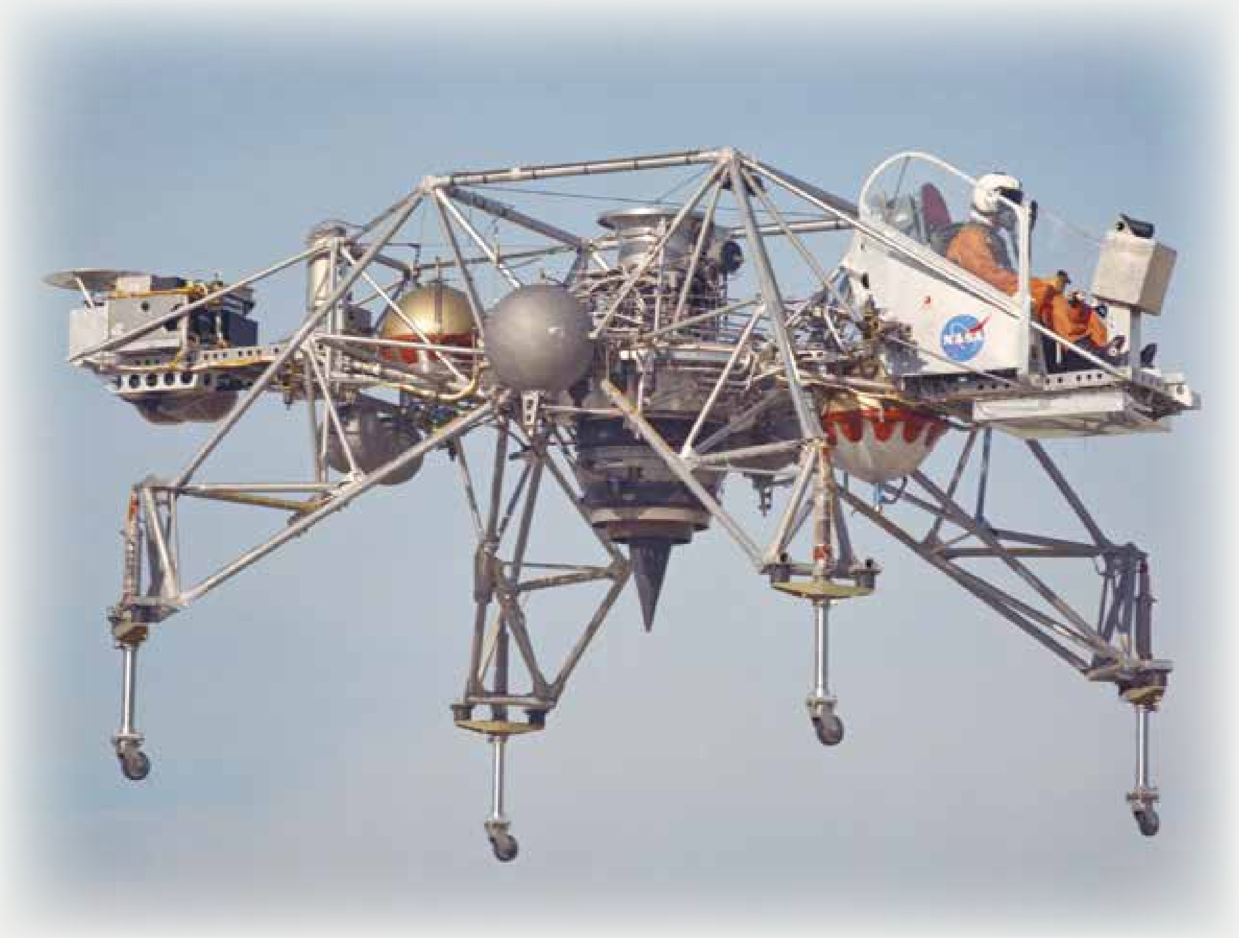
NASA

Throughout the 1950s, the projects undertaken by the NACA staff at Edwards were, as the name of the station indicated, focused primarily on the problems of high-speed flight. But in 1959, the NACA was absorbed into the new National Aeronautics and Space Administration (NASA), opening a whole new realm of exploration – and a whole new range of flight research requirements. Mirroring this expanded mission, NASA changed the name of the HSFS in 1959 to, simply, the Flight Research Center (FRC). The expanding NASA center at Edwards kept that designation until 1976, when it was renamed for the former NACA director who had talked about the role of flight in separating the real from the imagined: Hugh L. Dryden.

A mere five years after the center's renaming, however, NASA made yet another change, keeping its Dryden name but making it a subsidiary *"Flight Research Facility"* under the administrative direction of the Ames Research Center, located at the Moffett Field Naval Air Station in Mountain View, California. The uneasy marriage between the two centers lasted 13 years before NASA decided that Dryden really did operate more efficiently as an independent entity and restored its status as a full NASA research center.

All told, the Dryden Flight Research Center has undergone eight name and status changes in 60 years, more than any other NACA or NASA center[6]. But the numerous titles and affiliations over the years are, in many ways, reflective of one of its most defining characteristics: something center veterans call *"technical agility,"* or the ability to adapt and adjust resources to meet constantly changing needs. For while it didn't start out with that kind of flexibility as a goal, the Dryden Flight Research Center, along with the focus and organization of its research, has been a work in progress ever since those first 13 Langley employees arrived in Muroc in 1946.

A glance at Dryden's history, in fact, offers a remarkably good understanding of the nation's evolving and fluctuating priorities in aeronautics and space. Basic research in aerodynamics and propulsion is a critical precursor to any breakthrough flight research program, but the application of new concepts to a flight vehicle requires an even greater commitment and, therefore, greater financial and administrative support. As a result, projects that received funding at Dryden are a fairly accurate barometer of what the NACA/NASA administration, private industry, and the U.S. government regarded as important enough for the nation to pursue with its research dollars.



A Lunar Landing Research Vehicle in flight on December 1, 1964. The aircraft, which had a multi-axis thrust vectoring system, tested a number of the concepts of operating a landing vehicle in the moon's thin atmosphere. Later converted to Lunar Landing Training Vehicles, the odd-looking contraptions prepared the astronauts to land on the moon during the Apollo Program. (NASA photo EC64 0502)

At first, the small contingent from Langley had a single focus: to research the problems of transonic flight with the Bell X-1 and the Navy-sponsored Douglas D-558 Skystreak and D-558-2 Skyrocket aircraft. But the effort soon expanded to include research with a whole series of X-planes that explored new configurations for high-speed flight, and troubleshooting problems with new high-speed military fighters such as the F-89 and the F-100A Super Sabre.

By the 1950s, the nation was looking toward even higher-speed flight and space exploration, and Dryden embarked on research with what would become one of its most successful and high-profile aircraft and programs – the X-15 rocket plane – which explored the use of reaction controls in space, re-entry dynamics, and hypersonic flight. While a capsule shape was chosen for the vehicle for the emerging manned space program, Dryden expanded its support of NASA's space activities to include the testing of potential capsule parachutes, as well as landing systems flight research with the awkward-looking Lunar Landing Research Vehicles (LLRVs) in which Apollo astronauts practiced for a moon landing. A popular poster at Dryden reminds employees and visitors of the center's role in the moon program by showing one of the LLRVs in front of a full moon with the headline, *"Before we landed on the moon, we practiced here."*

Fly-by-Wire

But while the lunar program garnered much of the nation's attention during the 1960s, Dryden's innovative engineers were looking ahead to future space flight. With a small amount of discretionary center funding, research began on a series of wingless *"lifting body"* designs that proved the viability of a craft that could glide back from space, greatly influencing the design of the space shuttle and future space vehicles. At the same time, researchers at Dryden were beginning work on high-speed research projects with a Mach 3-capable Lockheed prototype YF-12 Blackbird and the XB-70 Valkyrie bomber, in support of the nation's burgeoning Supersonic Transport (SST) program.

As the country moved into the post-Apollo, energy-conscious era of the 1970s, Dryden's focus shifted once again. The SST program was dead, but the space shuttle program was just beginning. The airlines were looking for more fuel-efficient designs, and concern over general aviation accidents led to several Dryden research efforts to learn more about aerodynamic phenomena such as flutter and the possible effects of an aircraft's wake and wingtip vortices on an aircraft flying behind it.

NASA research pilots Milt Thompson (standing on ladder), Bruce Peterson, and Don Mallick (in front of Bruce) surround Air Force test pilot Chuck Yeager, who is seated in the cockpit of the wingless M2-F1 lifting body research aircraft. (NASA photo E-10628)

There was also a revolution brewing in aircraft design, although few could have foreseen just how far-reaching its effects would eventually be. For the early 1970s marked the beginning of the computer age. In 1972, Dryden flew the world's first digital fly-by-wire aircraft, proving dramatically that computers could be relied upon to run even flight-critical functions and opening up an entire new world of design and configuration possibilities. The advent of fly-by-wire stability and control meant that engineers could now build aircraft that were vastly more maneuverable, but too unstable for a human pilot to control, by relying on the plane's computer to provide adequate stability. Maneuverable fly-by-wire fighters ranging from the F-16 Falcon, the F/A-18 Hornet, and the new F-22 Raptor, as well as commercial airliners and business jets, were all influenced by Dryden's digital fly-by-wire research effort.

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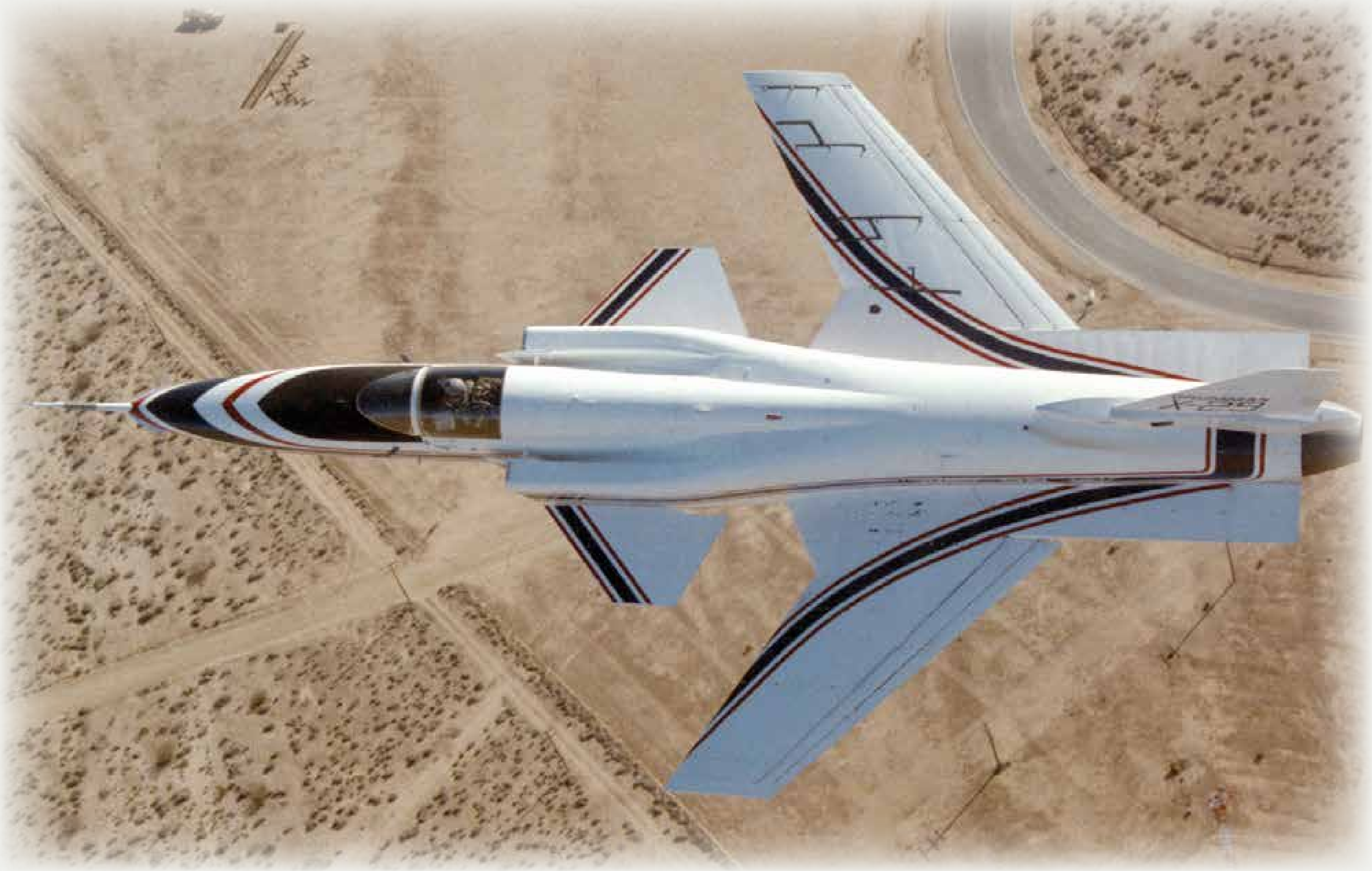
DIGITAL FLY-BY-WIRE
FLIGHT RESEARCH CENTER

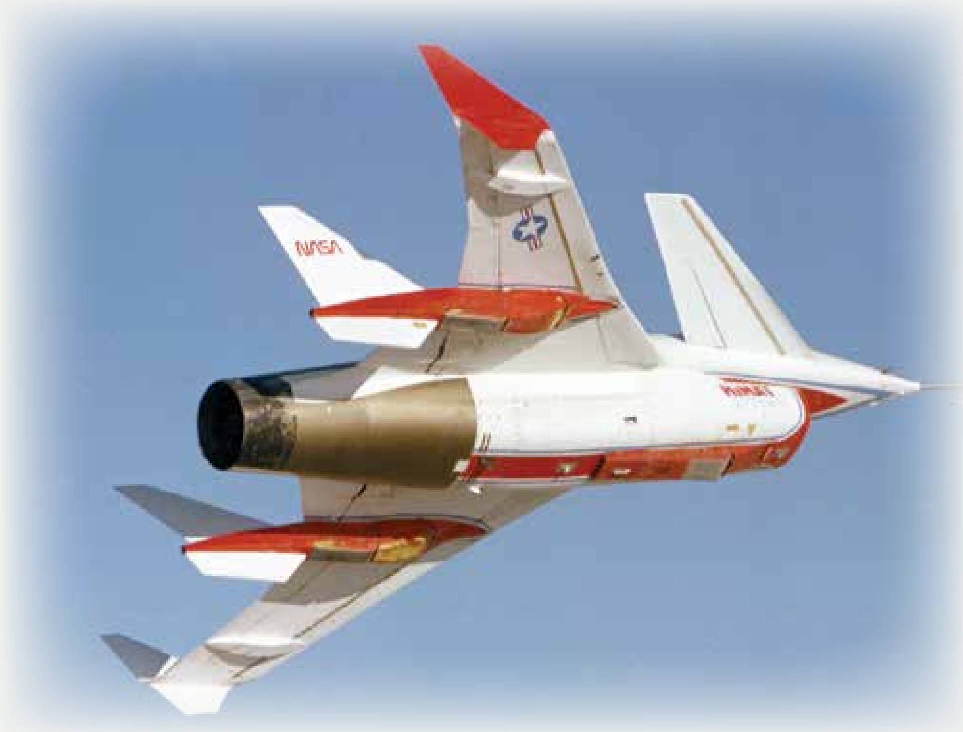
The F-8 Digital Fly-by-Wire aircraft in flight on October 27, 1972. The revolutionary flight research using this aircraft proved that computers could control flight-critical functions, permitting use of aircraft configurations heretofore not possible. (NASA photo EC72 3276)

HiMAT

Aircraft maneuverability was also becoming a much higher priority for the nation's military at that time. U.S. fighter aircraft had not performed as well against their adversaries in Vietnam as they had in Korea or WWII. Training might help improve that success rate in future conflicts, but more maneuverable aircraft could also give U.S. pilots an edge, especially in any potential Eastern European conflict. If Soviet fighters, which were becoming ever more capable and maneuverable, attacked along the border between Eastern and Western Europe, defense fighters from air bases in West Germany would be forced into close-in combat almost from the time they took off.



The X-29 forward-swept-wing aircraft in flight above the high desert on December 20, 1985. Two of these Grumman-built aircraft flew in an extended flight research project conducted in partnership among Grumman, the Air Force, and Dryden. A digital flight control system allowed these otherwise unstable aircraft to fly at high angles of attack (approximately 70 degrees for aircraft number 2) and to gather data on the loads, handling qualities, and buffeting of these unique airplanes. (NASA photo EC85 33297-064)



The Highly Maneuverable Aircraft Technology (HiMAT) in flight on December 15, 1980. This subscale, remotely piloted research vehicle designed by Rockwell International featured winglets, canards, digital fly-by-wire controls, and a composite structure. It was able to sustain 8g turns (compared with about 4.5g for an F-16) and was, indeed, highly maneuverable, allowing collection of data impossible on a piloted aircraft. (NASA photo EC80 14274)

This concern with maneuverability led to numerous projects at Dryden throughout the 1980s and early 1990s. There was a remotely piloted, jet-powered research aircraft called the *"HiMAT,"* for Highly Maneuverable Aircraft Technology, which investigated experimental technologies and configuration changes that might give aircraft greater maneuverability. The X-29 explored a range of advanced aircraft concepts, including the potential performance advantages of a forward-swept-wing design. The F-18 High Alpha Research Vehicle (HARV) program collected data to help researchers understand and more accurately model the flight dynamics of the extremely high angles of attack more maneuverable aircraft would encounter as well as being the first Dryden aircraft to investigate thrust vectoring. Two other Dryden research aircraft, the X-31 and the F-15 Advanced Control Technology Integration Vehicle (ACTIVE), looked at various applications and issues related to *"thrust vectoring,"* technology that would allow an aircraft to direct the thrust coming out of its engine(s) to achieve higher maneuverability.

At the same time, Dryden was still supporting the nation's efforts in space flight and exploration. In addition to its initial work in glide tests of the orbiter and critical support in troubleshooting a potentially lethal control-system glitch, Dryden continued to provide valuable research support for various aspects of the shuttle program. In addition to its role as first a primary and then a backup landing site, the center has conducted flight research on drag chutes, tires, thermal protection systems, solid rocket booster parachutes, and even post-accident testing of the foam insulation that caused the 2003 breakup of the Space Shuttle Columbia.

Access to Space

The F-15 Advanced Control Technology Integration Vehicle (ACTIVE) in flight April 14, 1998. This colorful aircraft, outfitted with canards, researched the use of an axisymmetric, gimballing nozzle to study thrust vectoring and advanced engine control. (NASA photo EC98 44511-014)

Ten years before the Columbia accident, however, NASA already was looking at follow-on programs to the shuttle. Under a new national *"access to space"* initiative, NASA and the aerospace community began research into several potential new space vehicle designs and a host of supporting technologies. The plans included building a technology demonstrator for a single-stage-to-orbit Reusable Launch Vehicle (RLV); a new emergency crew return vehicle for the space station; and several other lower-cost methods of putting small payloads into space. Dryden was involved in flight research pertaining to most of those vehicles, including the X-33 and X-34 technology demonstrators and the X-38, which was designed as an autonomous, emergency crew return vehicle that would glide back to Earth and then land under a steerable parachute. Dryden also participated in flight research supporting several other smaller launch vehicle concepts, including the air-launched Pegasus® rocket and a project called *"Eclipse,"* which looked at the possibility of towing a winged space vehicle aloft and then launching it into space, which could eliminate the need for a first-stage rocket.

Concurrently, Dryden was also conducting numerous experiments in high-speed flight in support of a High-Speed Civil Transport (HSCT) concept that NASA and industry were exploring together. Dryden's research ranged from mapping sonic boom patterns with an SR-71 Blackbird to exploring supersonic laminar flow possibilities with a cranked-arrow F-16XL aircraft. The center also revisited the realm of hypersonic flight during this time, successfully flying the first aircraft model powered by a supersonic combustion ramjet (scramjet) engine at speeds up to Mach 10 with an unpiloted X-43A test vehicle.

Yet not all of Dryden's work during the 1990s revolved around speed and space. Computer and fiber-optic technologies were opening a whole new realm of possibilities in terms of aircraft flight and engine control, and a variety of experiments with components and systems in this area that showed potential for improving the safety and performance of both commercial and military aircraft. After a total hydraulic failure caused the tragic crash of a United Airlines DC-10 airliner in 1989, a Dryden engineer designed and successfully demonstrated – first with an F-15 and then with an MD-11 airliner – a system that could fly and land an aircraft safely using only engine power for control. This was possible in large part because of previous work done at Dryden on its F-8 Digital Fly-By-Wire aircraft, which relied entirely on computers for flight control. Control by engine power alone was possible only through this fly-by-wire technology.

At the same time, the center was embarking on two new areas of research: airborne sciences and Unmanned Aerial Vehicles (UAVs). The primary impetus for Dryden's involvement in airborne sciences was a NASA Headquarters decision, in 1996, to relocate all the environmental research aircraft formerly operated by the Ames Research Center to Dryden. Dryden's initial interest in UAV technology, on the other hand, was actually as a means to gather data on high-altitude emissions for the HSCT program. But the search for capable UAV aircraft and technology soon put the center in a key, host role in an innovative, industry-driven UAV development effort known as the Environmental Research Aircraft and Sensor Technology (ERAST) program.

The low-speed, low-power, uninhabited ERAST aircraft, which were built and tested primarily by contractors, were not initially popular at Dryden, which was accustomed to piloted, higher-performance vehicles over which it had more quality and research control. But the program turned out to be far more significant than many people realized at the time and a harbinger of things to come, for UAV technology is becoming the next great revolution and era in aircraft design, and the ERAST program helped pave the way for this new generation of aircraft. Indeed, had it not been for the ERAST program, General Atomics would most likely not have had the Predator B UAV aircraft available for U.S. military use in Afghanistan and Iraq. At the same time, Dryden was also working with several different military adaptations of jet-powered UAV technology.

Proven its Value

The impact of this vast catalogue of research has been almost as diverse as the projects themselves. Sometimes the contribution was a small piece of technology, a design approach, or a new element or degree of accuracy in the basic aeronautical knowledge base. And sometimes, like the faint traces of pioneer wagon wheels that might still be found decades later, Dryden's contribution was simply to have gone into new territory first, exploring a new configuration or concept that was too advanced, risky, or expensive for industry to pursue on its own.

A C-141 towing a WQF-106 delta-wing aircraft in a Kelly Space & Technology, Inc. project to demonstrate the feasibility of launching a space vehicle from behind a tow airplane. This was one of many examples of partnerships between Dryden and other organizations. (NASA photo EC98 44398-10)

In some cases, such as Dryden's *"inertial coupling"* research with the North American F-100, a control system delay in the space shuttle orbiter, and the Lunar Landing Research Vehicle, research flights at Dryden led directly to critical vehicle improvements or pilot capabilities that saved lives and allowed missions to succeed. In others, such as the F-8 Digital Fly-By-Wire project, the impact was in giving industry the confidence to incorporate the new technology into production designs. The center's lifting body research of the 1960s did not lead directly to the development of a lifting body spacecraft, but it convinced shuttle designers that a winged spacecraft could, in fact, glide safely to a runway landing on Earth. The supersonic flight research of the 1960s and the SR-71 sonic boom research in the 1990s both were directed at supersonic airliners that were never built. But that research is now playing an important role in an effort to explore the possibility of building a supersonic business jet with an environmentally acceptable sonic boom footprint. Follow-on research for Dryden's Intelligent Flight Control Systems program was not initially funded, but the concept is now being pursued again because it might make aircraft less susceptible to missile attacks. Despite the end of the Cold War, and improvements in air-launched missile designs, both of which were supposed to make traditional close-in aerial combat a thing of the past, the thrust-vectoring capability developed with the X-31 and the F-15 ACTIVE has appeared on the Air Force's F-22 and Boeing X-45A Unmanned Combat Aerial Vehicle.

AeroVironment
ERAST
Pathfinder
NASA
Pathfinder

This Pathfinder Plus flying wing, built by AeroVironment, used solar power to operate at high altitudes. Shown here on June 17, 1998, the aircraft later (August 6) attained an altitude of 80,200 feet. As this photo shows, this lightweight, unmanned aircraft was part of the Environmental Research Aircraft and Sensor Technology (ERAST) program. (NASA photo EC98 44621-252)

Aerial photo of NASA Dryden Flight Research Facility (NASA photo EC92-10204-2)

A Unique Mix

Over and over again Dryden has proven its value not only in pursuing research to answer the current needs of NASA, industry, or the nation, but in imagining solutions to problems that haven't yet arisen. That kind of effort is harder to explain or justify to a budget-conscious administration or congressional committee, but it remains one of the strongest justifications for an independent research facility like Dryden to exist. For if we are to travel one day beyond the known horizon, we need explorers who are willing not only to imagine the future, but who can also gather the knowledge and develop the tools to help us get there.

A Unique Mix of Place, People, and Partnerships

Over the course of more than seven decades, Dryden has managed to adapt to an almost continuous climate of change while conducting a stunningly broad range of research projects related to current and future problems and possibilities in flight for both civil and military applications in both aeronautics and space. How has a single NASA center managed to become and remain such a flexible and useful resource for such a wide and changing set of priorities and projects? The answer seems to lie in a unique combination of three ingredients that have endured at Dryden throughout the changing winds of time, funding, technology, and external events.

The Place

The first critical ingredients are Dryden's ideal surroundings and facilities for conducting flight research projects. The same natural elements that attracted Hap Arnold and the Air Force to the Mojave Desert are still present, and still as important for flight research projects as they were in 1946. The arid weather and clear skies across some 12,000 square miles of special-use airspace, the open, uninhabited landscape, and the many dry lakebeds surrounding Dryden create an ideal environment for all kinds of flight efforts, from low-powered, lightweight UAVs to high-speed rocket research. Over the past half century, NASA and the Air Force have enhanced those natural resources with developments such as the Western Aeronautical Test Range (WATR), which can provide tracking and telemetry for low, high, and supersonic flight in an area that stretches from Edwards Air Force Base to Wendover, Utah.

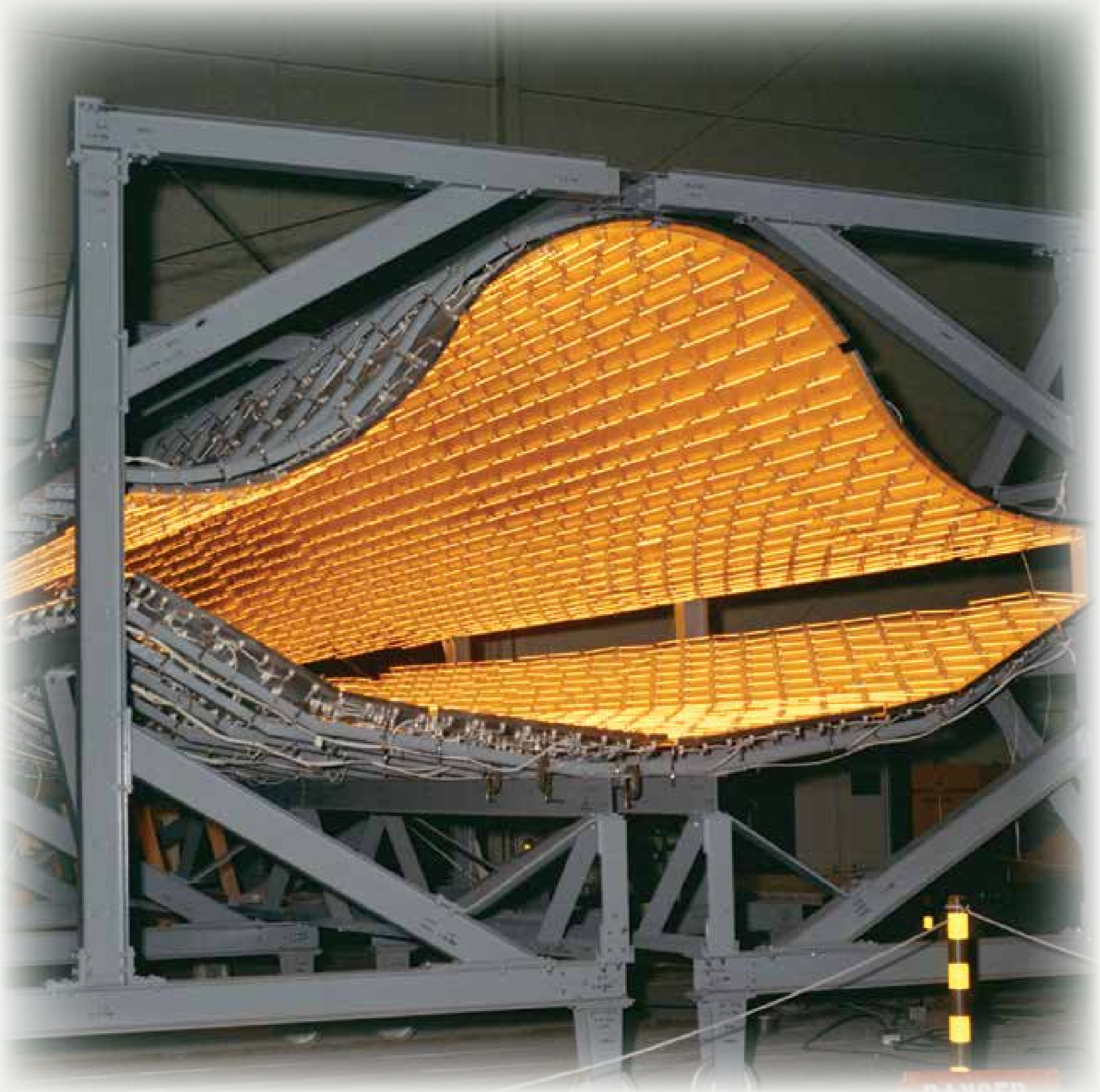
The Place

Ground facilities at Dryden have improved and expanded over the years. Dryden's current ground resources include a Flight Loads Laboratory that performs combined mechanical load and thermal tests of structural components and complete flight vehicles, a flow-visualization facility, two fully equipped control rooms, a data-analysis facility, a facility to conduct flight research with remotely piloted vehicles, and a unique Research Aircraft Integration Facility that allows both hardware-in-the-loop simulation and the integration and simultaneous pre-flight testing of aircraft flight controls, avionics, electronics, and other systems.

In addition, Dryden has developed and maintained a fleet of research aircraft that has often proved to have worth far beyond its initial missions. These aircraft are themselves national resources that have enabled numerous breakthroughs in technology, safety, and capability – research efforts that might never have made it to flight if Dryden hadn't had an aircraft available and instrumented for the job.

Software engineer Monica Garvin and systems engineer Dave Upton in the Developmental Lab testing the Western Aeronautical Test Range (WATR) Integrated Next Generation (WINGS) 2.0 system before it went into operational use in the control room to monitor flights and collect data. (NASA photo EC04 044-17)

The NB-52B *"mothership"* that was initially modified to drop the X-15 rocket plane from a pylon under one of its wings, went on to support an astonishing number of additional research missions, from a whole series of lifting body aircraft, to F-111 crew escape pods, to parachutes for the space shuttle solid rocket boosters, to the X-43 hypersonic research aircraft. The NB-52B carried so many different projects aloft, in fact, that its array of mission markings stretch more than halfway down one side of its fuselage. And yet none of those additional missions were envisioned when the plane was originally acquired and modified. By the same token, Dryden's F/A-18 Systems Research Aircraft, which began life as a chase aircraft but evolved into a highly flexible research platform, offered government and industry researchers a cost-effective way to research a wide variety of small components and systems in a high-performance, fly-by-wire aircraft. And one of Dryden's F-15Bs has evolved into a flying test bed, carrying a host of experiments and test equipment to speeds of Mach 2, a role not initially envisioned for the aircraft.



YF-12 forebody heater undergoing testing in the Thermal Loads Laboratory to support flight loads research on supersonic aircraft, April 29, 1971. At speeds up to Mach 3+, it was difficult to separate the aerodynamic from the thermal effects on the aircraft. Using data from the ground facility as well as flight, engineers collected an enormous database that led to methods for separating the aerodynamic from the thermal forces operating on an aircraft, of great importance for future supersonic and hypersonic aircraft. (NASA photo EC71 2788)

The People

The second ingredient in Dryden's continued relevance and success is, without question, the people who work there. As one Dryden manager put it, *"only the most dedicated human beings work here. Nobody comes out here for the scenery, the facilities, the proximity to [Los Angeles], or anything except total involvement with planes."*[7]

It's true. A passion for flight research, and pride in their work, runs deep in almost all the people who work at the Dryden Flight Research Center. Part of this intense level of dedication and focus is, indeed, a pre-existing motivation and love of flight that drives people to seek work at Dryden rather than in more convenient and scenic places. But another part of it has to do with Dryden's small size, and the isolation of its work force. Dryden is one of NASA's smallest centers. At its employment peak it had just over 1,000 people, and, since – aside from other military and civilian workers at Edwards Air Force Base – there is no other population center for at least 30 miles in any direction, the staff at Dryden tends to be a pretty close-knit community.

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The NB-52B mothership drops the M2-F3 lifting body on August 9, 1971. The M2-F3 was but one of many research aircraft launched at altitude from the NB-52. (NASA photo EC71 2774)

Left to right research pilots Joe Walker, Stan Butchart, and Walter Jones standing next to the Douglas D-558-2 Skyrocket with the P2B-1S mothership in the background (its role indicated by the stork painted on its side next to symbols for the research aircraft it had launched at altitude). (NASA photo E-676)

Another piece of the puzzle has to do with the work itself. Dryden's mission means that its workforce has a very practical focus around which all activities and efforts must revolve. Every employee can see, within one or two steps, the impact of their work on an actual aircraft. In addition, many of those aircraft have a pilot in them whose life quite literally depends on the accuracy and quality of the work the other employees have done. And because of the center's small size, that pilot is probably someone each of those employees knows personally. It's a powerful motivating brew. A mistake doesn't just mean an adjustment to a financial report the following quarter. It can mean carrying the burden of a lost aircraft or pilot from that day forward. And there have been planes and pilots lost. Throughout Dryden's history, ten piloted aircraft have been lost to crashes, and three pilots have given their lives in pursuit of research projects associated with Dryden.[8]

Indeed, those who work at Dryden are so acutely aware of the human consequences of mistakes that they tend to be very outspoken about their views. As Dryden employees often say, *"There are no secrets in flight research."* There cannot afford to be. It is not unheard of for researchers and technicians to work through the night to find a solution to a potential flight-stopping problem, and any project team member, from a research engineer to the pilot himself, has the power to stop a flight if he or she feels there is a safety-of-flight issue left unresolved.

Unique Way of Doing Business

All these factors – the center's small workforce, its remote location, the tangible risks and rewards of flight, and the unusual nature and demands of research and exploration itself – have distilled into what one center director called a *"unique way of doing business."*[9] From the early days, there were never quite enough people for the tasks at hand, so employees got used to being flexible and performing whatever job had to be done. In addition, the fact that the center was small and far removed from Washington, D.C. meant that Dryden had to contend with less bureaucracy and politics than did many other NACA/NASA centers. Even today, managers are likely to simply encounter people they need to consult several times in the normal course of their day, either in the halls or the center's small cafeteria. This allows an informal, face-to-face management and problem-solving style that is low on paperwork and still highly efficient and effective.

In truth, an innovative, problem-solving style is a virtual prerequisite to coping effectively with experimental aircraft. There are no established and proven maintenance manual procedures that cover how to solve an unexpected problem with an X-plane or an errant line of computer code in the world's first digital fly-by-wire aircraft. And if a problem arises at 8:00 at night and the airplane is scheduled to fly at 8:00 in the morning, the most important goal is to find a solution that works.

On November 16, 2004, avionics technicians Randy Wagner (leaning) and Terry Bishop make final adjustments to the supersonic-combustion-ramjet-powered X-43A unpiloted hypersonic research vehicle before its record Mach 9.6 flight the same day. (NASA photo EC04 323-53)

A thousand procedures can never take the place of experience. One of the greatest strengths Dryden offers in the field of flight research is the simple fact that those dedicated people who choose to live and work in the desert also tend to stay there for a very long time. As a result, Dryden has always had an enormous vault of corporate memory in its workforce – a memory that is as much a national resource as the center's research aircraft or ground facilities. This wealth of knowledge on earlier technology experiments and on how to conduct safe and successful flight research programs is actually one of the most valuable assets Dryden brings to any flight research project, whether it is an internal NASA effort or a complex partnership with industry and external institutions. When, for example, the Air Force and Kelly Space Technology, Inc. came to Dryden in the mid 1990s to discuss the possibility of towing a QF-106A delta-wing fighter behind a C-141A cargo aircraft to test a new space vehicle launch concept, they were able to gain valuable advice from engineers and pilots who had conducted tow experiments with the original lifting body aircraft in the 1960s.

That practical knowledge is a great help to any flight program, and there are any number of examples where Dryden's insistence on certain safeguards, procedures, or additional preparation has saved a research vehicle or enabled a troubled research effort to get back on track.

The Partnerships

The other critical ingredient in Dryden's continuing ability to make valuable contributions to industry and government is its ability to create partnerships and work as part of a research team. Team efforts are never as simple as individual pursuits, and each entails a new set of challenges, personalities, and innovative adaptations of policy and organization. But Dryden has a unique advantage in this area; the need to work as a team and in partnership is intrinsic to every project undertaken at the center.

From its first day of operation in 1946, the Langley-based Muroc flight test unit was faced with the need to work with partners. After all, the unit's work was being conducted on Air Force property, and the X-1 program itself was a joint effort of the Air Force, the NACA, and the Bell Aircraft Company. A lot has changed at Dryden as well as in the world since that time, but those basic partnership requirements have endured – and not just between Dryden and other agencies or contractors but even within Dryden itself.

The Partnerships

Many research organizations are organized by areas of specialization, allowing individual researchers to work for years within their own disciplines without having to even play with others, let alone play well with them, as the saying goes. That isn't possible at a place where the organizing principle of each researcher's effort isn't a discipline, but an aircraft. So although it retains a nominal organizational structure based on research disciplines such as aerodynamics, propulsion, structures, etc., Dryden has always relied on a matrix approach to its flight research programs.

A matrix structure creates a team of people from various disciplines to work on a particular project. Project teams typically include research engineers, operations engineers, and a project manager in addition to data systems engineers, technical, and support staff. Research engineers work on designing the experiments and analyzing the results, while operations engineers make sure the modifications will not compromise the integrity or safety of the aircraft. The project manager is responsible for keeping the project on schedule and budget, and coordinates the various efforts and work tasks. These three forces clearly have slightly different agendas, but they are designed to balance each other to keep research efforts both on track and safe.

Starr Ginn, left, and Natalie Spivey monitor systems during ground vibration testing for the F/A-18 Active Aeroelastic Wing research project. (NASA Photo EC02 203-64)

The YF-12A Mach 3 Blackbird aircraft in flight April 29, 1971. NASA flew these Lockheed-designed aircraft in partnership with the Air Force to gather data about high-speed aerodynamics, including thermal loads, propulsion, and other disciplines. (NASA Photo EC71 2708)

In addition to its internal need for multidisciplinary team building, Dryden's small size and the inherent nature of flight research also have meant that Dryden often must draw on the expertise and cooperation of other NASA centers, other government departments and agencies, research facilities, and industry partners in order to accomplish its research. Even the ideas that have flown at Dryden have actually come from a wide variety of sources: some were developed by Dryden's own research staff, others originated at university labs, other NASA centers, military research facilities, or even in private contractors' shops. Taking those ideas to flight, therefore, required a partnership between Dryden's flight research specialists and all the people and facilities that worked on the idea prior to that time. In addition, no matter what an idea's origin, flight research projects require hardware, which NASA is not typically in the business of building.

As a result of all of these factors, the center has always had to find ways to work well with external sources and partners. Some of those partnerships were fairly simple pairings, involving only Dryden and a single contractor, or Dryden and another NASA center. Others – such as the X-1, X-15, and X-29 projects – have involved one or more contractors, several NACA/NASA centers, and one or more branches of the military. The X-31 program involved not only U.S. contractors, the U.S. Navy, the U.S. Air Force, the Department of Defense's Advanced Research Projects Agency (DARPA), and NASA, but also the German Air Force and a German contractor.

Technical Passion

This is not to say that all those partnerships worked flawlessly from the beginning. On the X-1, for example, the Army Air Forces and the NACA had different objectives for the plane and its research. The NACA wanted to proceed methodically and gather as much data as possible, while the Army wanted to forge ahead and conquer the sound barrier as soon as possible. Indeed, one of the points of conflict Dryden still sometimes encounters with non-NASA partners revolves around the issue of differing priorities or standards for data collection, testing, safety, and review procedures. Dryden is sometimes criticized for being too rigid in terms of safety and review procedures, too cautious and burdensome in terms of the testing, data, and safeguards it demands prior to and during flight.

There are two sides to the argument, of course. Dryden is a research organization staffed by people with a driving curiosity for knowledge and answers that could be described as *"technical passion."* It's that passion that has allowed Dryden to make so many important discoveries and advances in knowledge and technology, and to develop so many creative solutions to aeronautical problems. But the flip side to that strength is that it can be difficult to rein in such a workforce, and get it to settle for obtaining only one piece of data when there is the possibility of collecting ten.

Dryden developed its stringent flight readiness review standards and procedures over 60 years of learning the hard way – through lost aircraft and pilots – the many pitfalls that can bring down an airplane or program. And the safety folks at Dryden are often correct in their evaluation of potential risk factors in a contractor or partner's research plan. But then Dryden's standards were developed for complex, piloted aircraft and programs; an irreplaceable, multi-million dollar research aircraft and the life of one or more human beings might be at stake in the event of a mishap.

A number of those elements are now beginning to change. In an increasing number of cases, the aircraft being tested at Dryden have no pilot on board. And some of the UAVs being flown there have much simpler systems, with fewer redundancies, than a research team would ever allow if a human life were at stake. At the same time, the variety of partnerships and work projects coming through Dryden's doors these days is also broadening. When the ERAST program agreement was hammered out in 1993-1994, Dryden's managers agreed to act as host for the industry-driven research flights, surrendering flight safety authority (with the exception of range safety) to the four industry participants, which meant making sure flight vehicles didn't put anyone on the ground at risk.

It was a kind of partnership that departed significantly from those the center had experienced up to that point but, despite initial concern on the part of many Dryden managers, the ERAST program turned out to be very successful. Several of the remotely controlled aircraft were lost in flight – but designers intended them to be far more *"disposable"* than the research aircraft flown at Dryden before. And the program accomplished its goals of advancing both UAV technology and a UAV manufacturing industry.

Photographed 1975 YF-12A (right) and YF-12C (left) in formation at dusk at the Dryden Flight Research Center. NASA photo ECN-4767

Dryden in the 21st Century

In today's changing world, Dryden faces a heightened need to broaden its working arrangements with an ever-growing number of partners. But adapting to new partnerships and teams is nothing new for anyone who's spent any time working at Dryden, for partnerships are as integral to the center's work as the aircraft themselves.

The aircraft flying at Dryden today may look different than those the original Langley contingent nursed into the sky in the late 1940s. But the combination of ingredients that made the initial research team so successful, and so valuable to the nation that led to it becoming a permanent research facility, is alive and well at Dryden today. The center still has ideal flight research conditions and irreplaceable research facilities, a passionate, creative, and dedicated staff that learned early how to work as a team with multiple partners, and a practical, problem-solving management style and focus. All those strengths will be needed in the years to come, because the mysteries and challenges of flight are far from vanquished.

Dryden in the 21st Century

In the 100 years since the Wright brothers flew their 1903 Flyer, we have learned much about flight. Exactly 32 years to the day after the Wright brothers' feat, the DC-3 – the first commercially viable airliner, which has defined the shape of airliners ever since – took to the skies. Less than 20 years after that, airliners entered the jet age. We now have military fighters that not only can fly supersonically but can cruise there without the use of afterburner, with power, stability, and flight control linkages provided by electronic computers. Even small-airplane pilots can now navigate by satellite and have access to real-time traffic, terrain, and weather reports in their cockpits.

From our first efforts to fly within our own atmosphere, we have discovered ways to leave it behind and land on the moon. We have regularly circled our own planet in a reusable craft capable of gliding back to a runway landing here on Earth, and a civilian-designed and built craft has even reached the edges of space flight.

And yet, for all that we've learned, there is much we still don't understand. Supersonic aircraft have been flying since the late 1940s, but as recently as 10 years ago, the manager of Dryden's supersonic laminar flow research program said, *"the more we get into this, the more I realize how little we really know about what happens in the transonic and supersonic regions."*[10]

In addition, the goal posts are continually moving farther away as our knowledge and capabilities expand. In 1946, researchers were simply trying to see whether it was possible for an aircraft to surpass the speed of sound and return safely. Today, the goals and challenges are broader. We want not just supersonic aircraft, but efficient, environmentally sensitive supersonic aircraft, or highly maneuverable, *"stealthy"* supersonic aircraft. Computers have revolutionized flight and navigation, but they bring with them a whole host of problems that didn't exist with simple tube and fabric aircraft designs. Computers have also enabled a whole new category of unpiloted aircraft that could expand our options for high-altitude, long-endurance, or high-risk flight missions, as well as provide new opportunities to explore, understand, and protect our planet's atmosphere and environment. But UAVs also bring with them new problems to be solved not only in the technology itself, but in integrating these uninhabited vehicles into the complex national airspace system as well.

We now know how to build efficient, reliable airliners, but we now have to examine new ways to protect them from terrorist attacks. We have developed the ability to reach and operate in space, but our goals are now not just getting off the planet, or even landing on the moon, but developing the technology to reach Mars. And where we once struggled to fly within our own atmosphere, we're now working on craft that can operate in the atmospheres of other planets as well.

All of these new challenges and opportunities will require advances in both technology and understanding. Exploring those new realms, and ensuring that any new technology really does function in the real world the way it was designed to do in the lab will still require those ideas to be researched and tested in flight, for the assertions of Wilbur Wright, James Webb, and Hugh L. Dryden still hold true.

Ground research facilities, computers, and simulation technology have advanced tremendously over the past half-century. But computers can only simulate what is known; the unknown is always unpredictable. A computer can extrapolate what should happen as a logical extension of what has happened up to that point, but the outcome cannot be assured until it is tested in real-world conditions.

Seventh Decade of Operation

For one thing, the external physics or conditions beyond any known speed, altitude, or flight environment may differ from expectation. But even elements that are understood individually may interact in an unexpected manner when they are brought together in a realistic environment. This is especially true for any aircraft that requires a pilot. Time after time, computerized flight control systems for aircraft have been tested successfully in simulators, only to exhibit different tendencies in flight. Part of the explanation for that difference is certainly the limits of simulators in modeling aircraft behavior precisely and replicating the unknown. But pilots also tend to react differently in a simulator – where even the worst mistake will cause them only embarrassment – than in an aircraft, where the stakes are far more serious and real.

In addition, flight still plays a critical role in separating real from imagined issues and problems in a new design, system, or technology. The same is true for the ability of a flight research program to instill critical levels of confidence in a new idea or technology among those who might integrate that concept into a practical system or vehicle.

In short, no matter how much we've learned about flight, or how far advanced our design technology has become, we still cannot explore new territory, ensure the real-world effectiveness of technology, or convince others to follow in what can seem like risky footsteps simply by sitting at a desk. We still need to explore, research, and test aerospace concepts in actual flight, in real-world conditions. Only then does the imagined truly become real. It was for this reason that the Dryden Flight Research Center was established in the first place, and it is why the center's facilities and efforts are as valuable to the nation today as they ever were.

In its seventh decade of operation, the Dryden Flight Research Center is once again facing shifting winds – winds that bring, as always, both challenge and opportunity.

For the moment, follow-on vehicles to the shuttle have been shelved in favor of a more far-reaching exploration challenge to return to the moon, reach Mars, and explore space. This new emphasis on space exploration has put pressure on NASA's aeronautics budget, but also brings with it new opportunities for innovative thinking and designs. For we cannot reach Mars, or even the moon again reliably, without advances in aerospace technology – advances that will require new and diverse flight research efforts.

The days of the *"Iron Men"* who took the X-1 and X-15 to the edges of space at speeds faster than sound may seem very distant as small, remotely piloted UAVs occupy an increasingly large focus in Dryden's research efforts. But those UAVs offer whole new fields in which Dryden can make valuable contributions, as UAV applications expand from environmental and military missions to those of search and rescue, forest service monitoring, and even homeland security. In addition, Dryden's established fleet of piloted research aircraft is also proving valuable for UAV studies. The center's F/A-18s, which offer the advantage of a pilot on board who can take over if a problem arises, have already been used to research automated-formation flight and refueling software that might be incorporated into future UAV designs.

In addition, recent and planned cuts to NASA's aeronautics budget, as well as a switch by NASA Headquarters to a policy of full-cost accounting and full-cost reimbursement have re-emphasized the need for Dryden to be even more active and flexible in working with outside agencies and customers. The center has always worked in partnership with other NASA centers, federal agencies, government departments, and private industry, and about a third of its funding comes from sources other than the NASA Aeronautics budget. But Dryden center leadership is now looking at ways of being more responsive to the varying needs of outside customers and more creative in partnership arrangements so the project mix can be shifted to include even more work with external partners.

These new financial pressures and changes are requiring ever greater levels of flexibility, innovation, and cooperation among Dryden's employees. And the process has not been painless or easy. But at the same time, a stronger outside partnership and project base will give Dryden a chance to become far less dependent on its Headquarters funding, and on the changing priorities of different administrations, for survival.

The future, in other words, will likely not be so very different from the past. At Dryden, after all, change is one of the only constants. But as the following chapters illustrate, throughout more than a half-century of changes and progress, Dryden's core character has remained essentially the same. It has always been a place steeped in experience, versed in partnership, and staffed by uniquely dedicated and passionate individuals who possess an astounding amount of what might be termed *"technical agility."*

New Directions

Those traits have enabled Dryden to continue making valuable contributions to NASA, the aerospace industry, and the nation for over 60 years. And no matter what other changes blow down the surrounding mountains or across the dry lakebeds of the Mojave Desert, the Dryden Flight Research Center will remain a remarkably flexible and agile center of expertise, where explorers and innovators can come together in conditions and facilities uniquely suited for flight research to step beyond the boundaries of what is known, and to discover the secrets and opportunities that lie in the uncharted realm beyond. It will remain a place where theoretical principle and real life come together, where discovery happens, where the imagined becomes real. And it will remain a place where dedicated individuals work to solve the problems of flight, opening doors to new worlds while helping provide better and safer lives for those who inhabit this one.

1 *"Some Aeronautical Experiments,"* presentation by Wilbur Wright to the Western Society of Engineers, (Dayton, Ohio, 18 September 1901).

2 Richard P. Hallion, "American Flight Research and Flight Testing: An Overview from the Wright Brothers to the Space Shuttle," paper from Dryden Flight Research Center Technical Library files, 18 September 1976, 18-19.

3 H.W. Withington to John P. Reeder, letter, 6 June 1979, from the files of the Advanced Transport Operating Systems office at the NASA Langley Research Center, Hampton, Virginia.

4 James R. Hansen, Engineer in Charge, (Washington, D.C.: NASA SP-4305, 1987), 1.

5 H. H. Arnold, Global Mission (New York: Harper & Brothers, 1949), 136.

6 As this discussion illustrates, the Dryden Flight Research Center has gone by numerous names throughout its 60-year history. But for the sake of continuity and ease of understanding, the center is simply referred to as "Dryden" throughout the book, regardless of the particular name it might have had at the exact moment a research project was being conducted.

7 Gary Krier, interview with author, Edwards, CA, 23 June 2005.

8 Manned NACA/NASA aircraft lost in the course of research or training flights at Dryden were: D-558-I, X-1 #3, X-1A, two F-104s, F-18, X-31, T-37, X-15, and a Learjet. Three NACA/NASA pilots have lost their lives in the course of flight research or training at Dryden: Howard Lilly, Joe Walker, and Richard Gray.

9 Kenneth J. Szalai, interview with author, Edwards, CA, 14 July 1995.

10 Marta Bohn-Meyer, interview with author, Edwards, CA, 22 August 1995.

The unusual-looking XB-70 Valkyrie taking off on July 27, 1965, for a research flight in support of the national Supersonic Transport program. (NASA photo EC65 0791)

Chapter 2

Flight's New Boundries

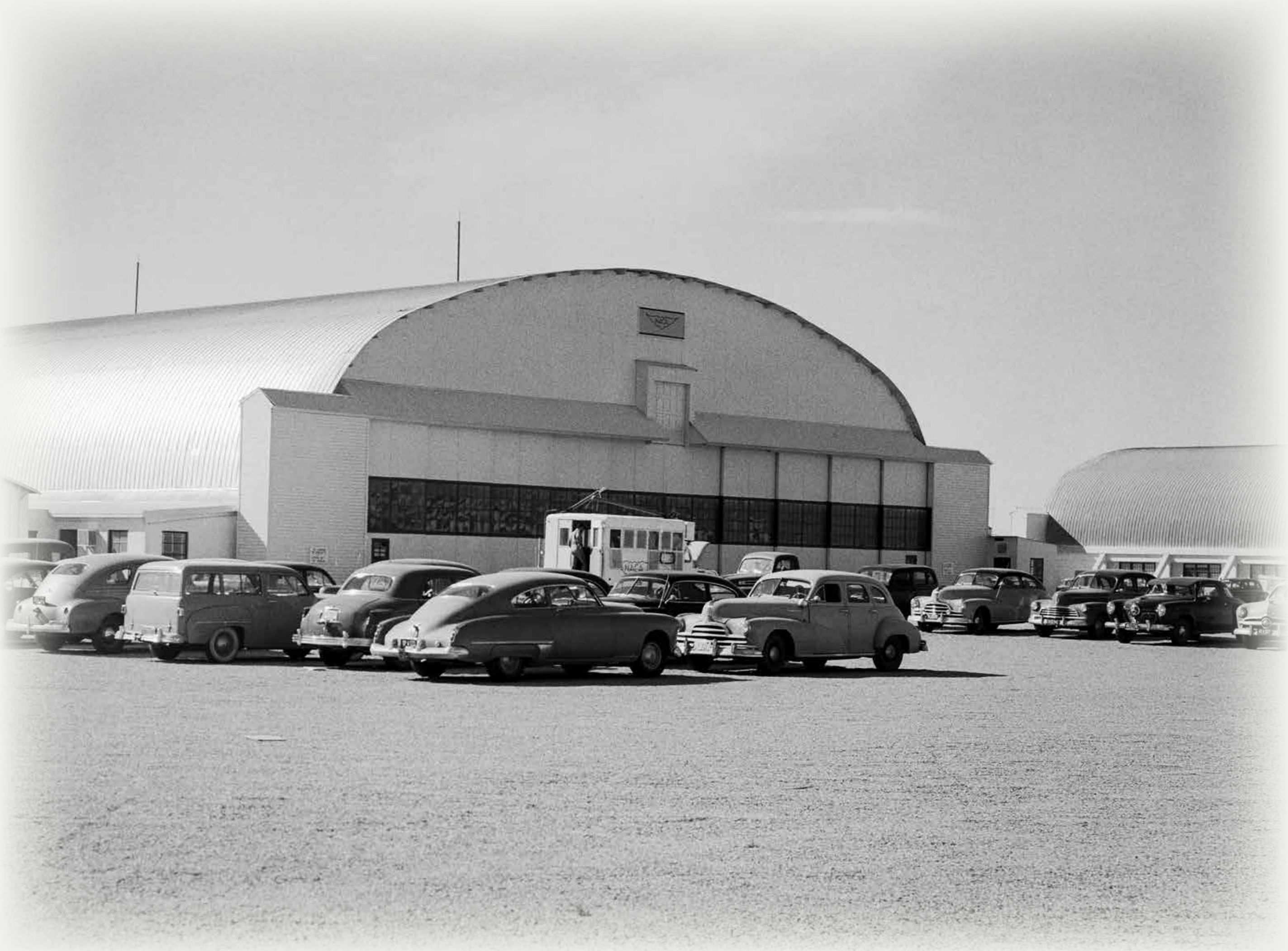
Mach 2 Dawn

by William W. Phillips

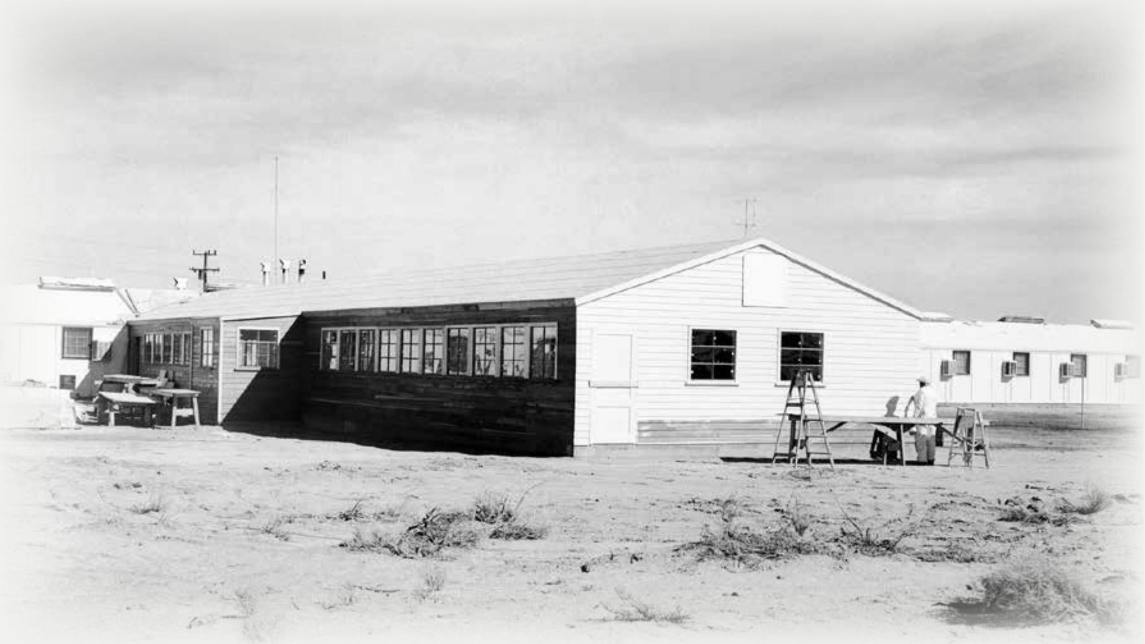
The NACA

When the NACA engineers arrived at Muroc from the lush, suburban Virginia landscape, they could never have foreseen the vast amount or range of work that their newly established desert base would undertake over the years. But from their first day on site, the group had to exercise the kind of adaptability and flexibility that would come to characterize the present-day Dryden. For the work environment and facilities the original Langley contingent encountered at Muroc were more akin to a military field operation than a national research institution.

For workspace, the NACA personnel were given part of one hangar at Muroc Army Airfield's South Base (there were two main hangars) and two small rooms for offices. The hangars were unheated and the desert sand and dirt blew through them constantly, creating an ongoing problem for technicians working with delicate instrumentation. Engineers frequently had to sweep a layer of dirt off their desks each morning before starting work. The flight test equipment available to the researchers was also a far cry from the sophisticated Mission Control facilities now associated with NASA. The *"control room"* for the X-1 flights consisted of a small, mobile van with a radar antenna, and a radio in the office of the chief of operations.

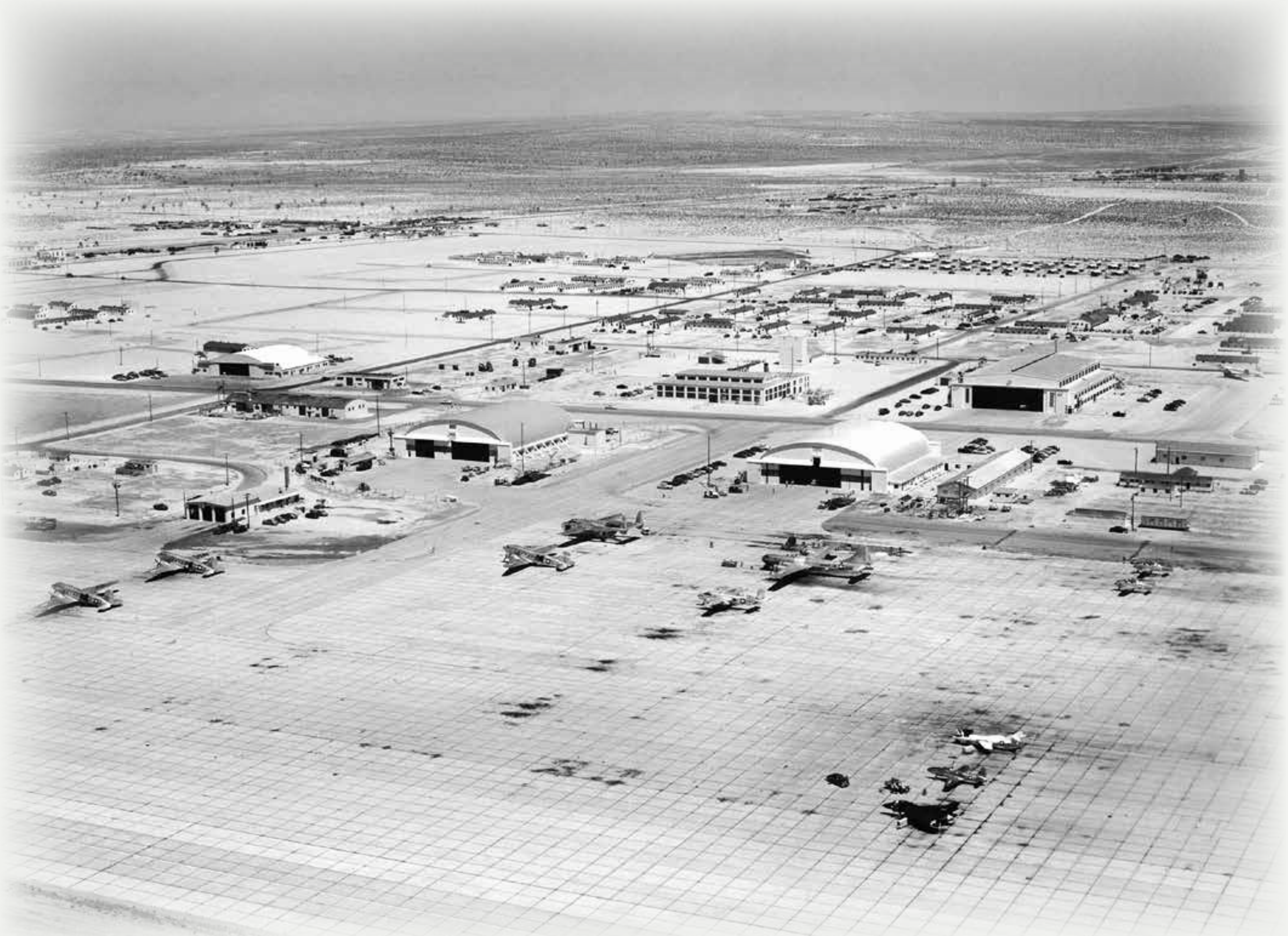


The NACA hangar and office building at South Base, February 15, 1951. (NASA photo E-441)



Men's dormitory, February 1951. This building reflected improved living conditions for the men working at the NACA High Speed Flight Research Station (as Dryden was called from 1949 to 1954) over earlier quarters, but the accommodations were hardly plush. (NASA photo E-432)

Living quarters for the NACA personnel were no better. Initially, the mechanics and engineers lived in a small shantytown halfway between the North and South bases. The cluster of firetrap buildings there became known as "Kerosene Flats," because all cooking and heating was done with kerosene. Heat was an unreliable element, however, leading a horrified visitor from Langley to report that the NACA employees at Muroc had *"the choice of working or going to bed to keep warm. Reading or writing in your quarters is impracticable because of facilities and temperature."*[1]



A view of Edwards Air Force Base's South Base facilities with the NACA hangar and adjacent office building in the foreground, July 12, 1951. (NASA photo E-503)

Breaking the Sound Barrier

Early photo of a D-558-1 Skystreak about to take off for a research flight. (NASA photo E-226)

The Langley contingent in those early years also included a number of women. Some worked as secretaries, but in those pre-automation days, research teams needed people with strong math backgrounds to reduce the raw data from flight instrumentation into a format that engineers could understand and process. These individuals, known as *"computers,"* were women and were a highly respected component of any research organization. The women from Langley were afforded a few luxuries the men h*ad to do without* – most notably, being allowed to eat at the base officer's club – but both men and women endured rough living and working conditions for their first eight years at Muroc/Edwards. In 1948, the NACA finally got permission to build new men's and women's dormitories but employees still had to share bathrooms, living rooms, and kitchens.

The bullet-shaped Bell X-1 beside the Boeing B-29 mothership in an early photograph. This was the thicker-winged X-1 #2. (NASA photo E-09)

And yet, the men and women who worked at the Muroc station took the inconveniences imposed by their surroundings largely in stride. In its isolation, the group acquired some of the close-knit characteristics typical of an *"ex-pat"* community of citizens living together in a foreign land. The NACA employees not only worked together but also socialized together, organizing group ski trips, picnics, and other weekend outings that led to more than a few marriages between single NACA staff workers at Muroc. But the bigger reason the NACA personnel were so willing to adjust, adapt, and endure the discomforts of their location was simply that they knew their work was of critical importance to the nation, and that they were being given the chance to help make history. A privilege like that was worth a certain amount of sacrifice.

Breaking the Sound Barrier

The work itself was, at first, focused on the X-1 research project. The X-1, a joint effort of the Army Air Forces (AAF), the NACA, and the Bell Aircraft Corporation, was built to get answers about flight in the transonic region (approaching and immediately surpassing Mach 1, or the speed of sound) that researchers were unable to get through conventional ground and wind tunnel tests. Aircraft design had progressed rapidly during World War II, but as high-performance fighters such as the Lockheed P-38 Lightning developed the capability of dive speeds approaching Mach 1, they began to encounter difficulties. Shock wave, or *"compressibility"* effects could cause severe stability and control problems and had led to the in-flight breakup of numerous aircraft. As the problems persisted, many people began to believe that supersonic flight was, simply, impossible.

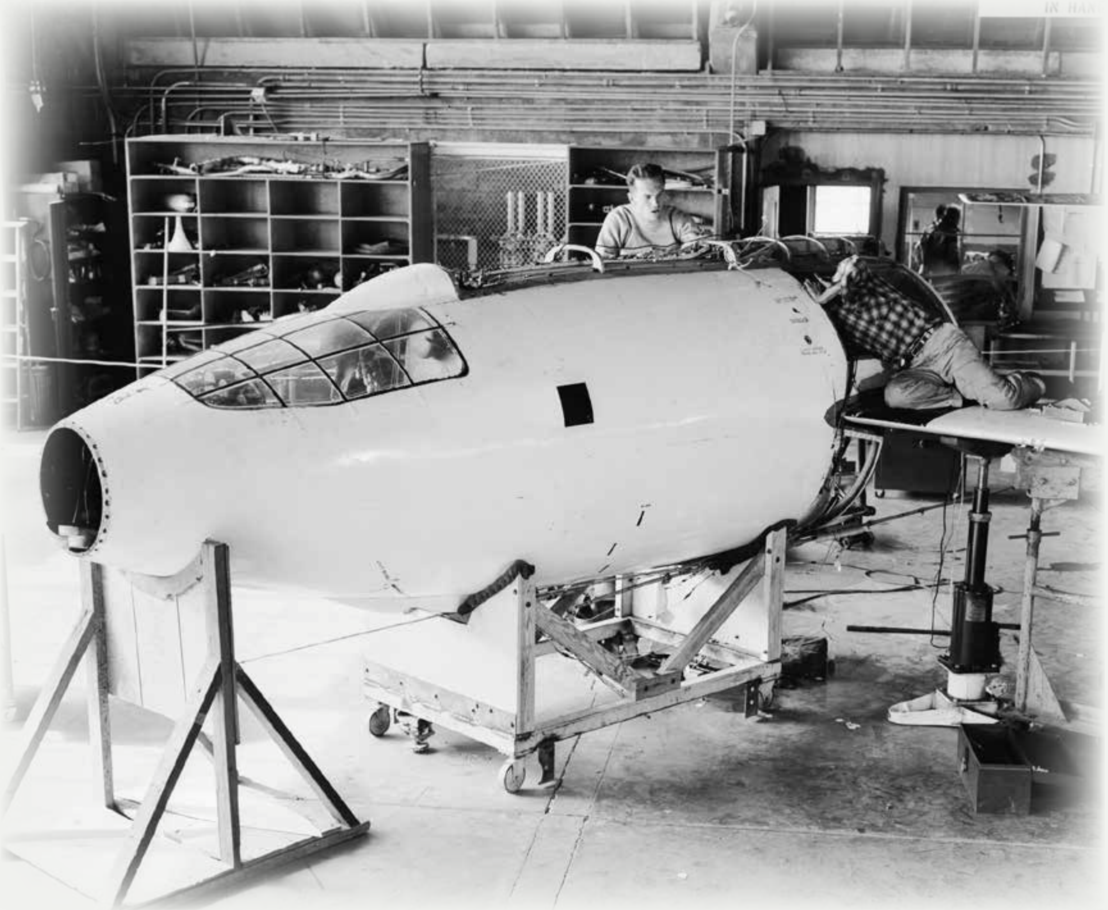
Early photo of the second, thicker-winged Bell X-1 on Rogers Dry Lake. (NASA photo E-02)

The X-1

Clearly, more information about flight dynamics at these higher speeds was needed, but that information was proving difficult to obtain. In the 1940s, no effective transonic wind tunnels existed, and other attempts at exploring transonic aerodynamics with rocket models and propeller-driven aircraft were proving unsatisfactory. The obvious solution seemed to be a purpose-built, experimental research aircraft that could reach and sustain transonic speeds long enough to collect firm data about flight in that realm.

Yet while the Navy, AAF, and NACA researchers all acknowledged the need for a research plane, they didn't agree on what kind of plane it should be. The Navy favored a jet-powered aircraft while the AAF wanted a rocket-powered design. The ensuing compromise entailed a two-pronged approach to solving the problem. The AAF and NACA teamed up with Bell Aircraft to build three models of the X-1 rocket plane, while the Navy and NACA worked with the Douglas Aircraft Company to create the D-558-1 jet-powered Skystreak. The Skystreak was expected to have lower performance than the X-1, but it was also seen as a less risky enterprise. By building both aircraft, the military and NACA figured they would increase their chances for success.

The X-1 was modeled on the shape of a 50-caliber bullet, which was one of the only shapes that had been proven capable of stable transonic or supersonic flight. The X-1's four-chamber, 6,000-pound-thrust liquid rocket engine would give it a mere 150 seconds of powered flight, which led to the decision to air-launch the aircraft from a modified Boeing B-29 Superfortress. In December 1945, just nine months after Bell Aircraft received an Army contract to build the plane, the first X-1 rolled out of the factory.

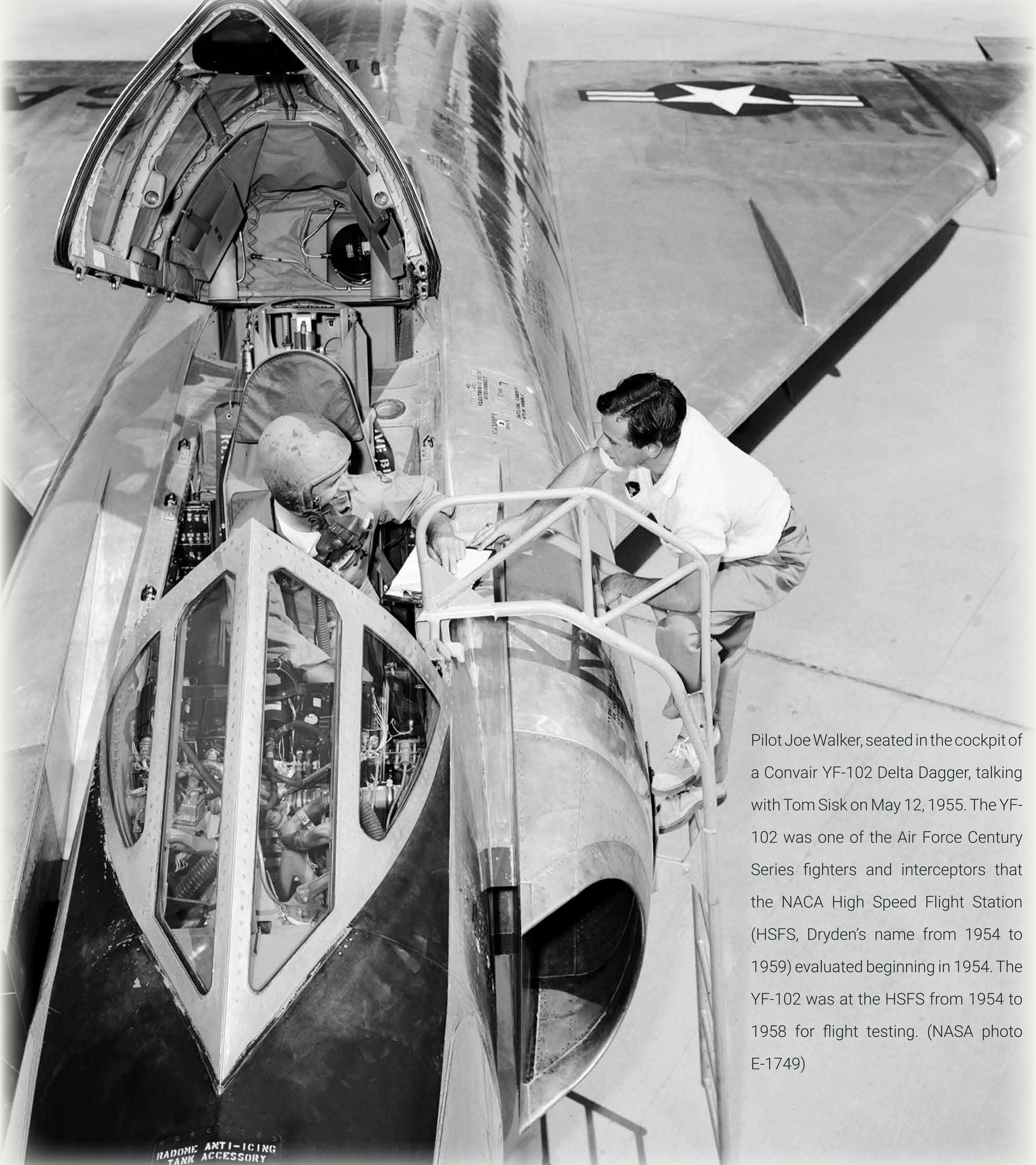


The thicker-winged Bell X-1 designed for thorough transonic research, partly disassembled with a view of the cockpit, November 19, 1950. (NASA photo E-397)

Initial glide tests of the X-1 were conducted at Pinecastle Field, near Orlando, Florida, which had one of the country's only 10,000-foot-long runways. But the location proved problematic, and Bell test pilot Jack Woolams and the test team quickly recommended that all powered flights be conducted at Muroc, where the team would have the advantage of clear skies, open landscape, and dry lake landing sites.

The first members of the NACA team arrived at Muroc on September 15, 1946, the second X-1 arrived a week later; even more arrived from Langley in October. The second X-1 was slightly different from the first model because it was designed to fulfill a different mission. The first X-1 was to be used by the AAF to make a focused, aggressive assault on the sound barrier and explore the aircraft's maximum speed and altitude capabilities. The second X-1, which had a thicker wing, was to be used by the NACA for more thorough transonic research. The NACA was responsible for providing instrumentation and technical supervision for all X-1 flights – a job made tougher by the rudimentary nature of the instrumentation available at the time. In addition to weighing 500 pounds, the X-1 research instrumentation was sensitive and susceptible to frequent failures, which caused problems on a number of flights.

Walter C. Williams on September 5, 1954. Williams was the first chief of the NACA organization that later became the Dryden Flight Research Center. He served in that capacity from September 1946 to September 1959. (NASA photo E-1364)



Pilot Joe Walker, seated in the cockpit of a Convair YF-102 Delta Dagger, talking with Tom Sisk on May 12, 1955. The YF-102 was one of the Air Force Century Series fighters and interceptors that the NACA High Speed Flight Station (HSFS, Dryden's name from 1954 to 1959) evaluated beginning in 1954. The YF-102 was at the HSFS from 1954 to 1958 for flight testing. (NASA photo E-1749)

Speed of Sound

But a bigger challenge with the X-1 program, as with many partnership efforts, was finding an effective way to divide tasks and proceed effectively as a team, despite the differing goals and approaches of the individual partners. The AAF wanted to push ahead and get past the magic Mach 1 mark as quickly as possible. The NACA, on the other hand, wanted to make sure it got as much data as possible from every flight. Seven decades later, this tension between speed and thoroughness, often mixed with concerns about budget and safety, is still a topic of debate within most research efforts, and striking the right balance among those factors is an ongoing challenge for anyone working in the field. Flight research is expensive and potentially hazardous, and there are goals and milestones to reach with as little cost in time and money as possible. And yet, it's also critical to get the data right, and accomplish the flights safely.

There is no one single solution to getting the balance among these competing needs right. Over the years, having learned many lessons the hard way, researchers at Dryden have developed a thorough set of flight readiness review procedures to ensure the safety of each research flight undertaken. And yet, even those tried-and-true procedures may not be appropriate for lower-risk projects, such as research flights with uninhabited vehicles. In other words, no matter how projects and technologies change, tension among speed, thoroughness, budget, and safety remains. And each flight research team has to work out its own answer to that equation, based on the unique needs and circumstances it faces.

In the case of the X-1 team, the partners were aided by a shared belief in the importance of the project's overall goal: to first reach and then learn how to master this mysterious world of flight at the speed of sound. In today's high-speed jet world, it may be difficult to fully appreciate just how elusive that goal seemed to those attempting to reach it in 1946 and 1947, but the challenges faced by the AAF, NACA, and Bell Aircraft team were immense.

The researchers and pilots involved with the project were convinced that supersonic flight was possible, but they knew things could go wrong. One year earlier, in 1946, Geoffrey de Havilland had been killed in a British D.H. 108 Swallow while attempting to break the sound barrier. And as the X-1 team began to nudge its way closer to Mach 1, it too began to encounter troubling phenomena. Ten years after the X-1's successful supersonic flight, Walt Williams, founding chief of the Muroc NACA Flight Test Group, recalled that the closer they came to their objective the more the group *"developed a very lonely feeling as we began to run out of data."*[2]

Mach 1

On a flight in early October 1947, the Air Force's primary X-1 pilot, Capt. Charles *"Chuck"* Yeager, achieved an indicated airspeed of Mach 0.94 but found that when he pulled back on the control stick, nothing happened. The speed had created a shock wave on the surface of the elevator, rendering it useless and leaving him with no pitch control. Yeager recovered by shutting down the engines and reducing his speed, but the incident taught the researchers the value of a movable horizontal stabilizer. Yeager solved the control problem by using the elevator to control the X-1's pitch at subsonic speeds but relied on small trim adjustments of the entire stabilizer at speeds near or past Mach 1. This discovery was so critical to high-speed flight that by late 1949, power-driven adjustable stabilizers had become standard equipment in new transonic-speed military fighters.[3]

But there were other difficulties. On a flight only four days before the team successfully broke the sound barrier, the X-1's canopy frosted over during Yeager's descent. Chase pilots had to talk Yeager down to a blind landing on the lakebed. To prevent a recurrence of the problem, crewmembers coated the X-1's windscreen with Drene® shampoo – just one illustration of the desert team's ability to find creative and effective solutions to unexpected problems.

Bell X-1 #3 about to be attached to the Boeing B-50 mothership, November 8, 1951. The following day, on the second flight of this X-1, it was destroyed in an explosion, and the B-50 was also lost. (NASA photo E-594)

Douglas D-558-1 Skystreak in flight, October 1951. (NASA photo E-713)

Finally, however, success burst across the desert with a sound that is now an everyday occurrence there: the telltale boom of a plane breaking the Mach 1 mark. On October 14, 1947, flying with two broken ribs, Capt. Yeager took the X-1 to a speed of Mach 1.06 at 43,000 feet, proving for the first time that a piloted aircraft could successfully surpass the speed of sound, making the sound *"barrier"* a myth of the past.

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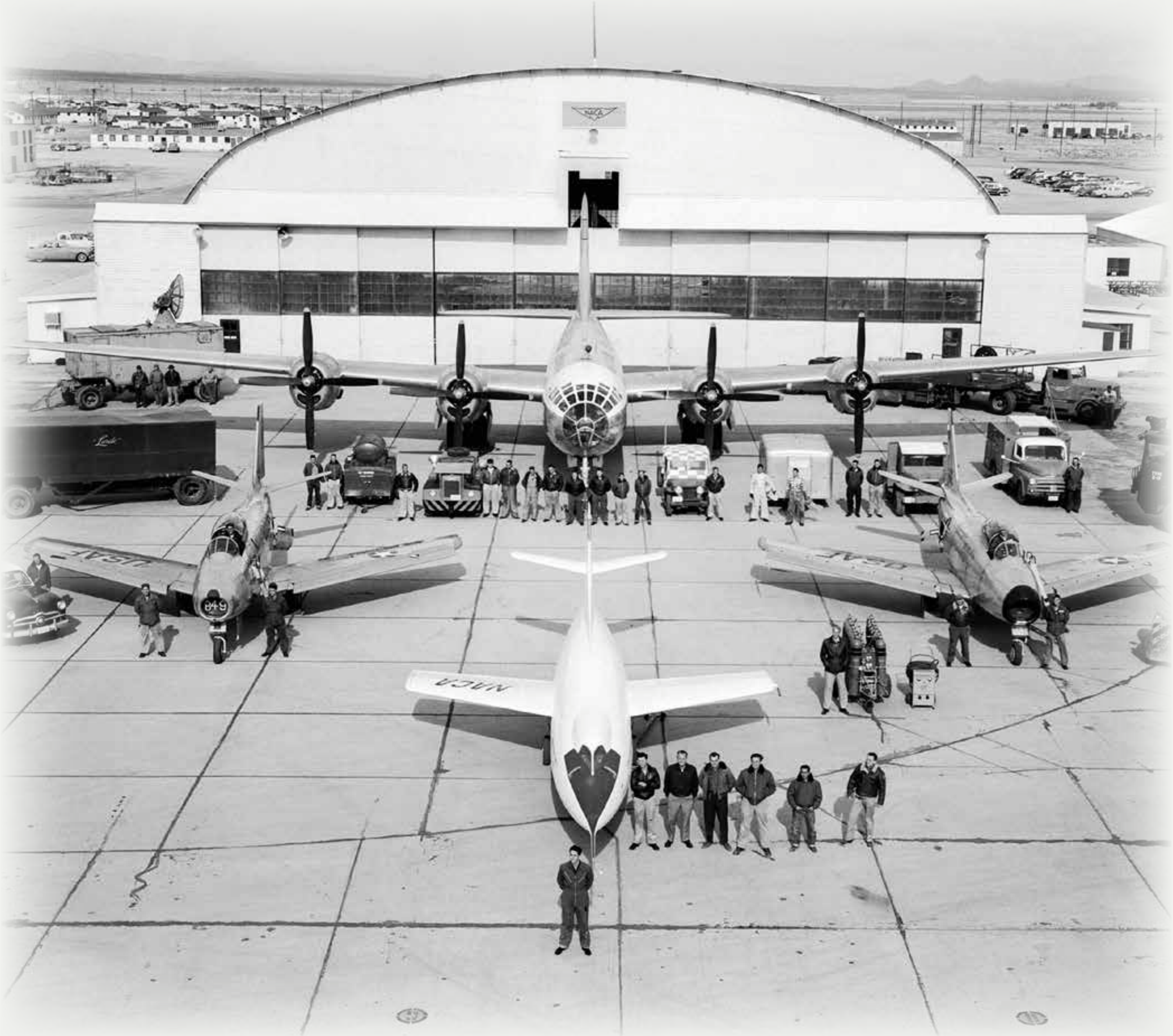
Engine run of a D-558-2 Skyrocket at the NACA High Speed Flight Research Station (as the Dryden Flight Research Center was then called), February 1, 1952. (NASA photo E-643).

New Research Aircraft

The breaking of the sound barrier was by no means the end of the road for the NACA group, however. The milestone just marked the end of the one short era in Dryden's history when the center's staff had the luxury of focusing on a single research project or aircraft. The Muroc NACA team began research with the second X-1 one week after Yeager's Mach 1 flight, and the first Navy-sponsored Douglas D-558-1 Skystreak arrived on site to begin flight tests in November that same year.

The three X-1 aircraft and the D-558-1 essentially comprised Dryden's first generation of high-speed research aircraft, and valuable information was gained from all of them. In March 1948, NACA pilot Herbert H. Hoover became the second man to fly beyond the speed of sound, although the thick-winged X-1 also showed researchers how great the penalty small changes in a wing could incur. The second X-1, which had a 10 percent thickness/chord ratio in its wing, turned out to have 30 percent more overall drag at transonic speeds than the first, thinner-wing X-1 used to break the sound barrier.[4]



Aircraft, people, and equipment used for NACA pilot Scott Crossfield's Mach 2 flight. Crossfield stands in front of the D-558-2 Skyrocket. Flanking and behind the first Mach 2 aircraft are two North American F-86 Sabre safety chase aircraft. Next to the hangar at South Base is the P2B-1S mothership that launched the Skyrocket for its record-breaking flight. In the upper right, and in between the hangar and a side building, is a portion of the X-3 fuselage. (NASA photo E-1152)

NACA technician working on the instrumentation of the Douglas D-558-2 Skyrocket, August 1952. (NASA photo E-790)

Technician working on the Convair XF-92A, August 1952. (NASA photo E-791)

Mach 2

While the lower-performance D-558-1 took a back seat to the X-1 aircraft, it also broadened researchers' knowledge about flight in the transonic range – particularly in demonstrating the value of vortex generators (small vertical airfoils aligned with the air flow and attached to the upper surface of the wing) to reduce drag and improve performance at high speeds. The idea of adding vortex generators to the Skystreak came from a researcher at Langley and, in a typical example of the Muroc unit's independent, non-bureaucratic, and innovative style, Walt Williams simply instructed his technicians to try it out. The small tabs they glued on the Skystreak's wing increased its speed in level flight by .05 Mach and helped to alleviate some of the buffeting and wing-dropping tendencies the aircraft had shown at those speeds. The vortex generators proved to be such an effective aerodynamic aid that they were subsequently incorporated into Boeing's new B-47 design. Since then, vortex generators have been used to improve the performance of air flow over the external surfaces – and even the engine inlets – of many production aircraft.

Pilot Joe Walker, left, next to a Northrop X-4, talks with engineer Donald Bellman, November 7, 1952. (NASA photo E-839)

Bell X-1A on the Rogers Dry Lake, June 1, 1955. (NASA photo E-1793)

The advancements in knowledge and technology came at a cost, however. NACA pilot Howard *"Tick"* Lilly was killed in May 1948 when the Skystreak he was flying suffered a catastrophic failure of its jet engine compressor on takeoff. The third X-1 and the B-50 launch plane carrying it were also lost in a post-flight explosion and fire following a captive (no-launch) test flight. The accidents served as additional reminders of a truth that was already well known to pilots and engineers: exploration at the far reaches of established capability and beyond the realm of what was known was not for the faint of heart.

But the effort continued with the second generation of high-speed research aircraft. Even before the first D-558-1 Skystreak was delivered to Muroc, the Douglas design team had come up with a more advanced version of the aircraft that included two important changes. The new D-558 was a swept-wing aircraft that incorporated both a jet engine and a rocket engine in order to increase its versatility. The redesigned plane was called the D-558-2 Skyrocket, and the first model joined the flight line of research aircraft at Muroc in 1948. That aircraft was followed by two more Skyrockets, one of which was subsequently modified for even better performance. Douglas removed the plane's jet engine to make room for extra rocket fuel and then reconfigured the Skyrocket for an air-launch instead of a ground takeoff. The changes paid off. On 20 November 1953, NACA pilot Scott Crossfield took the modified Skyrocket to an altitude of 72,000 feet and a speed of Mach 2.005, becoming the first person to fly more than twice the speed of sound.

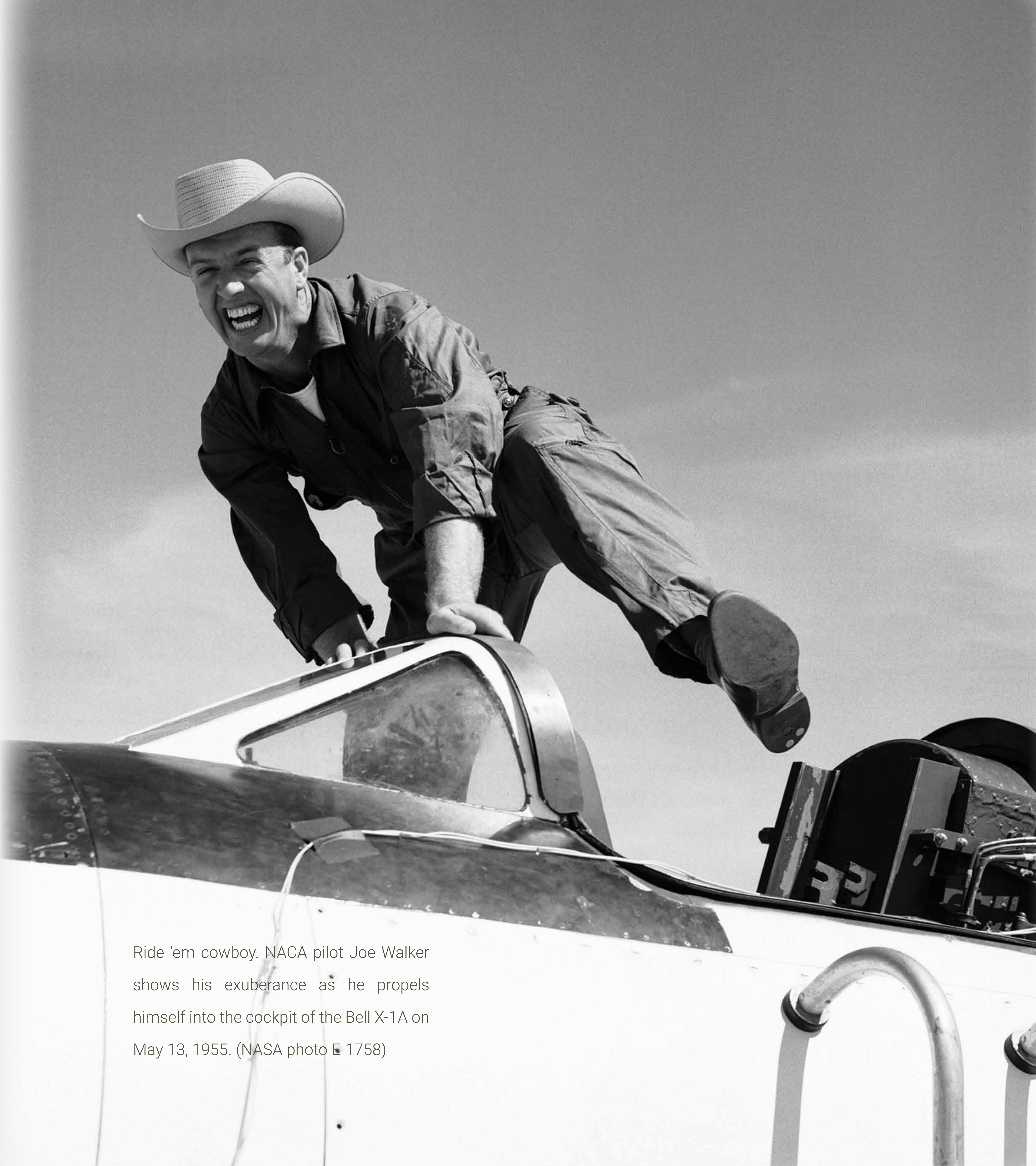
New Generation of X-1

Complementing the D-558-2 designs were several follow-on versions of the X-1, designated the X-1A, the X-1B, and the X-1D. An X-1C was designed but never built. Together with the even more capable X-2 design, the follow-on X-1 and D-558 aircraft were developed to explore higher speeds and altitudes, both to help manufacturers build aircraft that could operate in that realm and to provide information useful for future space flight. At the same time, the AAF and NACA commissioned the building of three additional research aircraft – the X-3, the X-4, and the X-5 – to explore the behavior of various configurations in transonic flight. A fourth configuration research aircraft, the XF-92A, joined this group after the Air Force[5] cancelled the proposed XP-92 interceptor aircraft the XF-92A was originally designed to support.

The X-1 derivatives had greatly expanded capabilities compared to those of the original X-1 design. They had larger tanks for rocket propellant and an improved fuel system. They were also equipped with ejection seats, which the original X-1s did not have. But the expanded family of X-1 aircraft was plagued with problems – a sharp reminder that the NACA and Air Force research teams were still operating at the very edge of capability and knowledge.

The first new-generation X-1 aircraft to arrive at what was now Edwards Air Force Base was the X-1D. It arrived in mid-1951, but its career was brief. On what was to be its first powered flight, the aircraft exploded while still attached to the B-50 launch plane. The X-1D's pilot, Maj. Frank K. Everest, managed to get back into the B-50 safely, but the stricken X-1D had to be jettisoned. The accident ended the X-1D program before it began and set the X-1A and X-1B programs back almost two years.

The X-1A finally arrived at Edwards in 1953 but it, too, soon encountered problems. The X-1A had been designed for speeds in excess of Mach 2, but it began suffering from severe stability problems as it approached its design speed. In December 1953, five days before the 50th anniversary of the Wright brothers' first powered flight at Kitty Hawk, Air Force pilot Chuck Yeager set a new speed record of Mach 2.44 in the X-1A, only to lose control of the aircraft immediately after reaching that mark. The X-1A gyrated wildly for 70 seconds, losing almost 10 miles in altitude before it slowed to a subsonic speed and went into an inverted spin, from which Yeager was able to recover. Of the next 14 flight attempts by Air Force test pilots with the X-1A, only four were successful. The NACA began its own research flights with the plane in July 1955, but on the second flight, there was an explosion in the aircraft just before launch. Like Maj. Everest, NACA pilot Joe Walker managed to get out of the plane safely, but the X-1A had to be jettisoned into the desert, ending the X-1A program.



Ride 'em cowboy. NACA pilot Joe Walker shows his exuberance as he propels himself into the cockpit of the Bell X-1A on May 13, 1955. (NASA photo E-1758)

The X1-E

The destruction of the X-1A and the X-1D left a gap in the Air Force/NACA research aircraft program. So in yet another example of the ever-present resourcefulness and innovation of the NACA team in the desert, the High Speed Flight Station staff led an effort to redesign one of the original X-1 planes to fill the gap. A thinner wing and lower-pressure fuel system made the resulting design, dubbed the X-1E, capable of speeds above Mach 2. Also in true NACA style, the X-1E was designed with far greater data-gathering capabilities. The NACA team imbedded 343 strain gages into the X-1E's wing for structural and heating data, as well as 200 pressure-distribution measurement openings.[6]

B-29 mothership with X-1E mounted beneath it just before taxi for takeoff on the X-1E's first captive flight, December 3, 1955. (NASA photo E-2082)

On January 27, 1953, several leading officials at the NACA High Speed Flight Research Station break ground on new facilities for the station. From left to right, Gerald Truszynski, Joseph Vensel, Walter Williams, and Marion Kent, plus California state official Arthur Samet) (NASA photo E-908)

New buildings of the NACA High Speed Flight Research Station (to be redesignated the High-Speed Flight Station on July 1, 1954). This photo, taken on May 18, 1954, shows the basically completed construction, which cost $3.8 million. With additions, these buildings still form the core of the NASA Dryden Flight Research Center. (NASA photo E-1254)

Supersonic Jet Age

The X-1B and the X-1E flew from 1955 to 1958 and were used to gather data about the forces exerted on an aircraft at high speeds and altitudes, including the effects of aerodynamic heating. Aircraft that could fly hypersonically, or above Mach 5, as well as potential spacecraft, were already in the planning stages and engineers needed information on the flight environment and forces those new designs would encounter. And although the X-1B and the X-1E were both capable of even higher speeds, neither was flown above Mach 2.3 because of the instability problems encountered with the X-1A. On the other hand, the X-1B was useful in exploring the use of reaction controls on several research flights that were, presciently enough, conducted by Neil Armstrong, then an NACA research pilot. Reaction controls, which used short bursts of pressurized gas to control or change a vehicle's yaw, pitch, and roll, became the primary mechanism for controlling a craft in the virtually airless environment of space.

And yet, at the same time as they were exploring the far reaches of speed and altitude, the NACA flight research team was also working on configuration research that offered critical and nearer-term benefits for the burgeoning jet aircraft industry. From 1950 to 1956, NACA and Air Force pilots used the X-3, the X-4, the X-5, and the XF-92A to explore the transonic behavior of different potential aircraft designs. In addition, the NACA team provided research support for production fighter designs that were encountering puzzling and deadly problems as they reached into the unfamiliar realm of high-speed flight. For with the dawning of the supersonic jet age, new production aircraft were beginning to push into the same flight envelopes as those research pilots were exploring with the X-series aircraft at Dryden. And as pressure to get new aircraft into service increased, the NACA's assistance became increasingly important.

A Northrop X-4 on the ramp at the NACA High Speed Flight Research Station, August 1950. (NASA photo E-359)

Group aircraft photo in front of the NACA hangar at South Base (Convair XF-92A in back; left to right in front, Douglas D-558-2 Skyrocket, Douglas D-558-1 Skystreak, Bell X-5, Bell X-1, and Northrop X-4). (NASA photo E-682)

One of the earliest production aircraft programs with which Dryden assisted was the Northrop F-89. The F-89 was a high-priority air defense program, and the Air Force had placed an order for more than a thousand of the jet aircraft. But in early 1952, six of the new F-89s lost their wings in flight. The accidents pointed to a serious flaw in the aircraft's design and put the entire program in jeopardy. Air Force and Northrop engineers began an intense effort to determine the cause of the accidents and asked for Dryden's help. Dryden engineers put strain gages on an F-89 and conducted a series of research flights to evaluate in-flight loads on various components, especially the wings. The flights uncovered the culprit of the airplane's problems: a weakness in a particular area of the wing's structure. Northrop redesigned the F-89's wing, and the updated fighter went on to a long and useful service life in the Air Force.

An early photo of a D-558-2 Skyrocket being towed across the Rogers Dry Lake. (NASA photo E-221)

Configuration Research

Meanwhile, Dryden researchers were moving forward on their own configuration research. The X-3, X-4, X-5, and XF-92A aircraft all had very different designs, each one aimed at exploring a different problem or design challenge in the transonic realm of flight. The X-3 was a long and slender aircraft that shared many design characteristics with new supersonic fighters being produced by the aviation industry. It had a thin, short wing and most of its mass concentrated along its long fuselage. The Northrop X-4 was a small, semi-tailless design similar to the World War II German Messerschmidt Me-163 rocket plane and the de Havilland D.H. 108 Swallow that had killed Geoffrey de Havilland in his attempt to break the sound barrier. The Bell Aircraft X-5 had a variable-sweep wing, and the Convair XF-92A was a delta-wing aircraft that bore a not-coincidental resemblance to the manufacturer's later F-102 and F-106 interceptor

FERTILE MYRTLE
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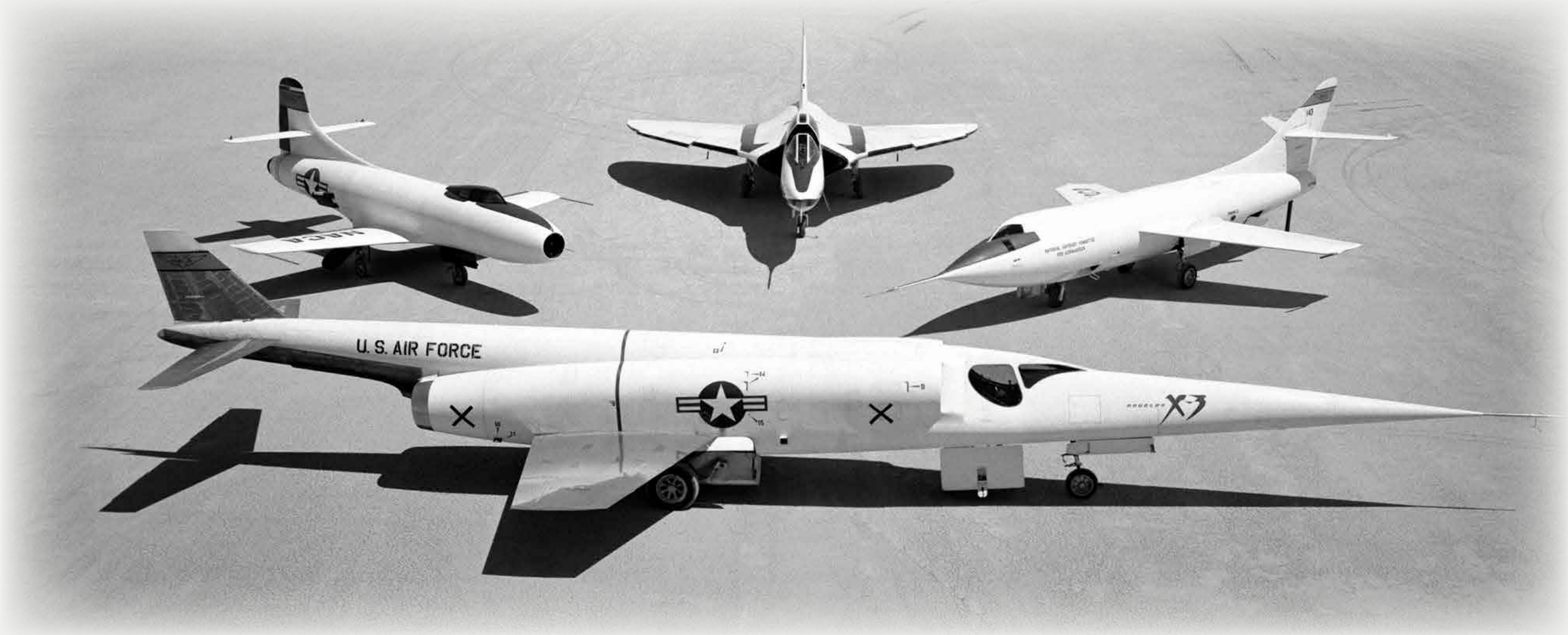
Nose art and D-558 mission markings on P2B-1S mothership, June 1956. The stork and "Fertile Myrtle" designation indicated the "mothership" or launch-vehicle role of the converted bomber, known to the Air Force as the B-29. The aircraft's mission markings adorn the fuselage. (NASA photo E-2344)



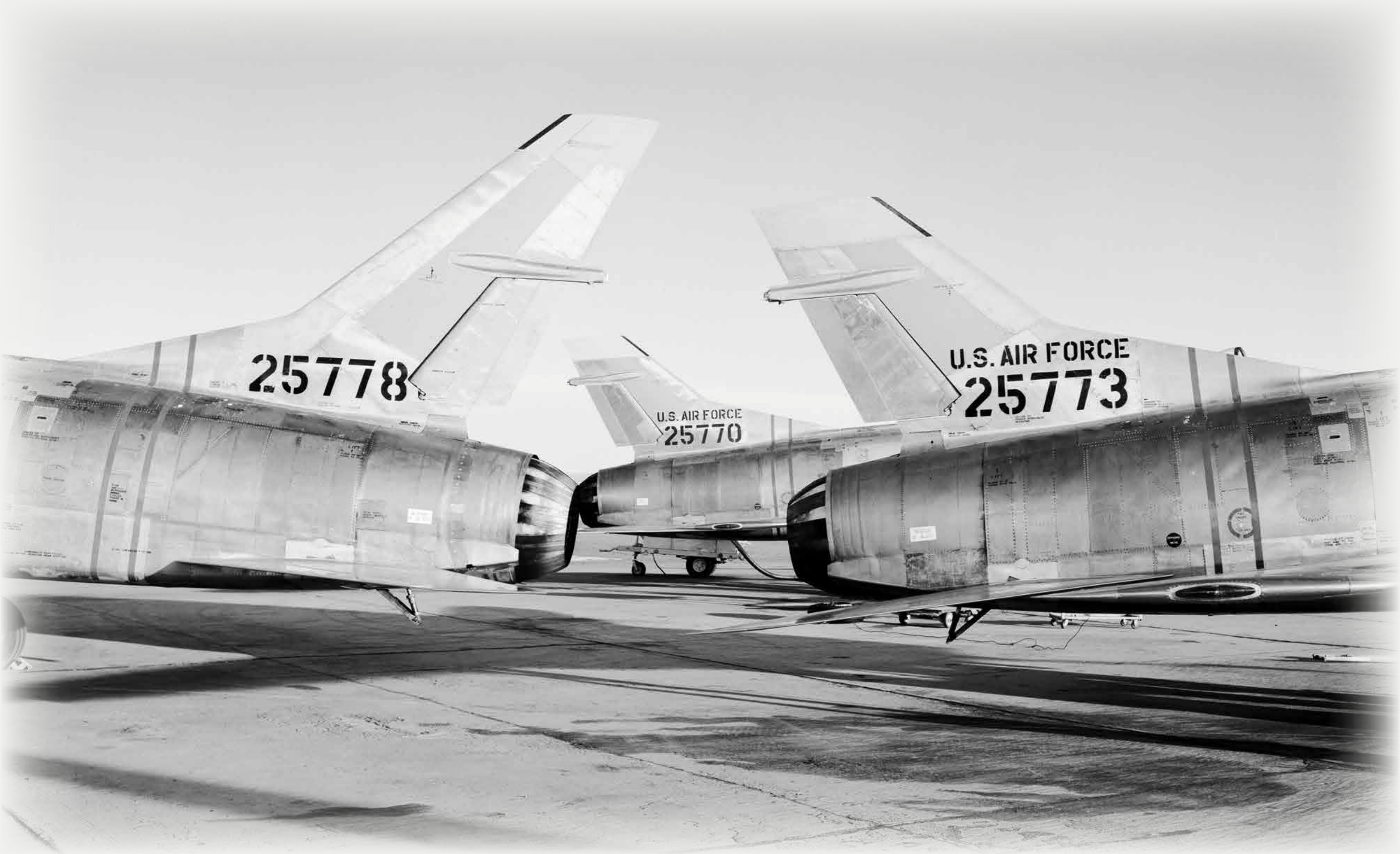
Group photo of several aircraft on the Rogers Dry Lake (clockwise from the front: the Douglas X-3, Douglas D-558-1 Skystreak, the Douglas XF4D-1 Skyray, and the Douglas D-558-2 Skyrocket). (NASA photo E-1239)

All of the *"configuration"* research aircraft exhibited unique quirks and problems, but all made important contributions to the aerospace industry: the X-4, for example, oscillated severely about all three axes as it approached Mach 0.9, convincing researchers that a semi-tailless configuration was altogether unsuitable for transonic or supersonic aircraft. That conclusion, however, proved a useful piece of knowledge for industry aircraft designers. As Gen. Jimmy Doolittle said, *"In the business of learning how to fly faster, higher and farther, it is sometimes very important to learn what won't work."*[7] The X-4 also was useful in gathering information on descent profiles for future space planes, because the X-4 had large speed brakes that could be deployed to give the plane a lift/drag ratio similar to that of a lifting re-entry spacecraft such as the X-15.

The Bell X-5, with its variable-sweep wing, was another troubled design. It had vicious stall/spin characteristics that caused NACA pilot Joe Walker to lose 18,000 feet recovering from a stall during one flight and eventually killed Air Force test pilot Maj. Ray Popson. But its problems were determined to be design flaws of the X-5, not the concept of a variable-sweep wing. On the contrary, the X-5 was instrumental in proving the feasibility of the variable-sweep concept. It also allowed researchers to learn a lot about the dynamics involved with that configuration throughout the transonic range.

The F-100A

The remaining configuration aircraft explored and addressed two of the most significant problems cropping up in the new generation of high-speed fighter aircraft. In abrupt maneuvers or at slow speeds, the noses of new swept-wing fighters tended to pitch up violently, often causing loss of control. The NACA researchers explored potential fixes for this problem with both the XF-92 and the D-558-2. The best solution for a *"conventional"* configuration like the Skyrocket, they determined, was to place the aircraft's horizontal tail low and far back on the fuselage, to keep it out of the disturbed airflow and downwash caused by the swept wing. As a result, the recommended low-tail configuration became standard on production supersonic aircraft such as the F-100 Super Sabre and the Vought F8U Crusader.



A pair of F-100As showing the initial configuration (left) and the modified version (right). In its original configuration the F-100A suffered from inertia coupling. The larger tail and increased wingspan solved the deadly tendency for the aircraft to go out of control during roll maneuvers. (NASA photo E-1574)

For delta-wing supersonic aircraft such as the XF-92A, which lacked a horizontal tail, a different solution was needed. The best fix for a plane like the XF-92A seemed to be wing fences running chordwise, from the leading edge to the trailing edge, to help keep air attached and flowing straight back across the wing, even at slow speeds and in tight maneuvers.

Yet the pitch-up problem paled in comparison with another difficulty NACA researchers, and a few unfortunate F-100 fighter pilots, were discovering with the new supersonic-aircraft designs. The technical term for it was *"inertial coupling"* or *"roll divergence,"* but to the pilot it meant the airplane had a tendency to go suddenly and violently out of control during rolling maneuvers. The F-100 jet was the nation's first fighter designed to fly past Mach 1 in level flight, and it had just gone into full production in 1954 when the inertial coupling problem surfaced. Inertial coupling already was a suspected cause in several accidents that had claimed the lives of F-100 pilots by the time NACA pilot Joe Walker experienced the phenomenon with the sleek-looking X-3 research aircraft.

The X-3 had been designed for sustained Mach 2 jet-powered flight, but the aircraft's engines were so underpowered it couldn't even attain Mach 1 in level flight. Yet its thin, short wing and elongated fuselage made it susceptible to inertial coupling, and the extensive instrumentation on the X-3 allowed researchers to collect valuable data on the causes and potential solutions for this new and deadly problem. During one particularly eventful research flight in October 1954, Joe Walker encountered such wild pitching oscillations in the X-3 during high-speed maneuvering that the aircraft reached its structural load limits before he could get it safely on the ground.

The X-3 research at Dryden was complemented with research flights in production F-100 aircraft from the North American Aviation factory. Engineers at both North American and Dryden suspected that the cause of the instability was insufficient wing and tail area, and North American was already considering a larger tail design as a possible fix to the problem. The Air Force and the NACA successfully pressured North American to reduce the production time on the company's new tail design from 90 days to nine, and Dryden began an intensive, high-priority flight research program, first defining the F-100's roll coupling problem and then evaluating the effect of various modifications, including the larger tail.

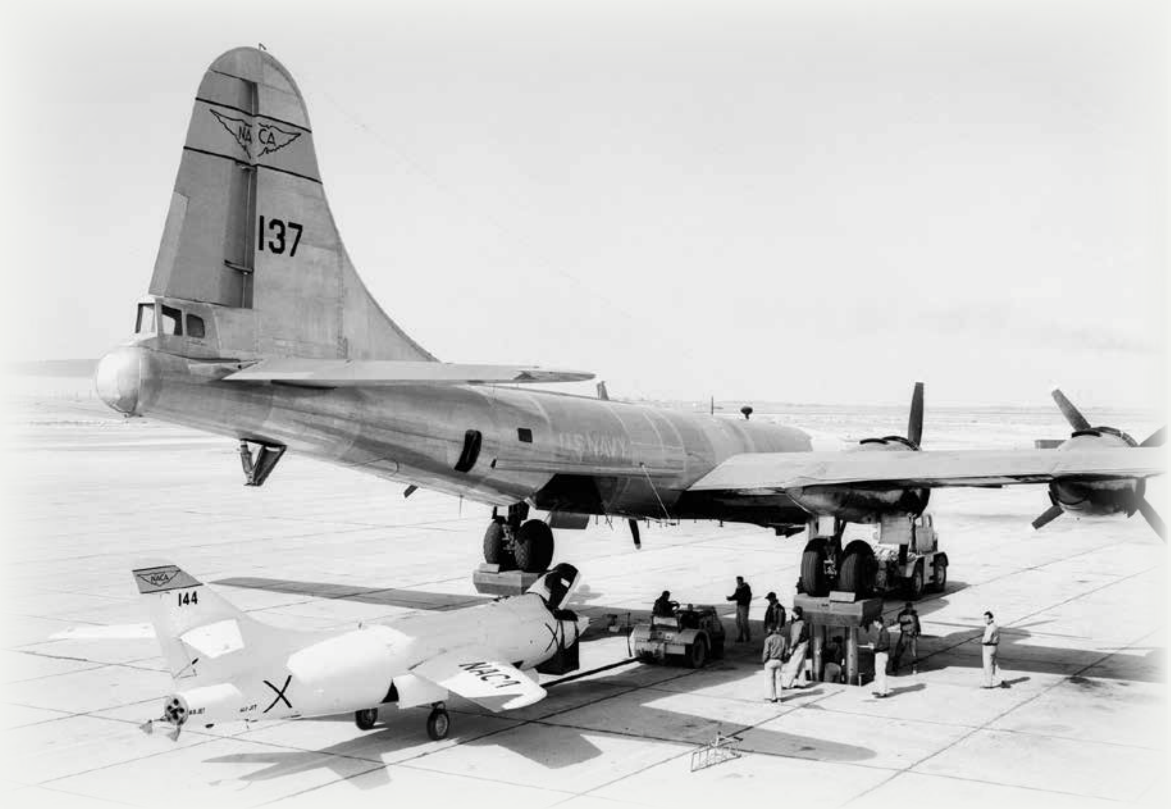
Mach 2 and Beyond

The F-100 flight program was not without risk or difficulties. On the first research flight at Dryden, pilot Scott Crossfield made an emergency landing after an engine-fire warning. The F-100 was not a docile aircraft, and North American's pilots considered an unpowered, or *"deadstick"* landing in the fighter extremely risky because of its high landing speed and poor glide performance. Nevertheless, Crossfield elected to try and land the airplane, and he executed an almost flawless approach and landing on Rogers Dry Lake, a testament to his piloting skills. If only he'd left it there. But Crossfield's confidence was so buoyed from the landing that he decided to attempt a precision stop in front of the NACA hangar, which was situated just to one side of the lakebed. Unfortunately, he didn't realize that he had used up the aircraft's emergency braking power. Crossfield coasted off the lakebed, up the ramp, and then, unable to stop, continued right through the open doors of the NACA hangar. He managed to miss the irreplaceable X-planes parked inside, but he ran the nose of the F-100 through the hangar wall. For years after that, the chagrined Crossfield joked about how Chuck Yeager had broken the sonic wall, and he had broken the hangar wall.

In the end, however, the research flights in the X-3 and F-100 aircraft solved the roll coupling riddle. The problem was, in fact, insufficient tail and wing surface area. North American immediately incorporated more wing area and a bigger tail into its F-100A design, turning the once-problematic design into a highly effective supersonic fighter. But the knowledge gained through the X-3 and F-100 flight research affected far more than one aircraft design. That data has been applied in one form or another to virtually every supersonic fighter built since.

Mach 2 and Beyond

As Dryden's first decade of operation drew to a close, the U.S. was in the throes of the Cold War. If American technology could allow us to fly higher and faster than existing Russian fighters – including even the possibility of flight in space itself – it would improve the nation's defense capability. As a result, aircraft research priorities in that era revolved around speed, altitude, and even more speed.



Douglas D-558-2, aircraft #2, about to be loaded into its P2B-1S launch aircraft in August 1953. This was the same Skyrocket in which NACA pilot Scott Crossfield exceeded two times the speed of sound (Mach 2) on November 20, 1953. The P2B-1S was the Navy's designation for the B-29. (NASA photo E-1013)

The technological progress that made such dreams possible was moving ahead at a staggering pace. In 1946, flying Mach 1 seemed a distant goal. But only seven years later, NACA pilot Scott Crossfield shot through twice that speed in the D-558-2 Skyrocket. And even before Crossfield broke Mach 2, the NACA, the Air Force, and private industry were looking at research and production aircraft that could fly even higher and faster than that.

The Bell X-2 was one of these. The streamlined X-2 was designed to investigate the problems of aerodynamic heating, stability, and control at speeds of Mach 3 and altitudes between 100,000 and 300,000 feet. To make the plane more heat-resistant, the X-2 was constructed out of stainless steel and a nickel alloy, and powered by a Curtiss-Wright rocket engine with more than twice the thrust of the X-1 family rocket engines. But the X-2 turned out to be a trouble-laden design, and its research career was short and deadly.

The first X-2 exploded during Bell Aircraft's own flight testing, killing the pilot and one of the launch plane crewmembers. The second was delivered to the Air Force for flight testing in August 1954 – flights conducted in partnership with the Dryden team, just as those with the X-1 and other X-plane flights had been. After a troubled start to the research program, the Air Force/NACA team finally completed several successful flights with the aircraft. And on 7 September 1956, Air Force Captain Iven C. Kincheloe successfully took the X-2 to an altitude of 126,200 feet, prompting Popular Science to dub him the *"First of the Spacemen."*

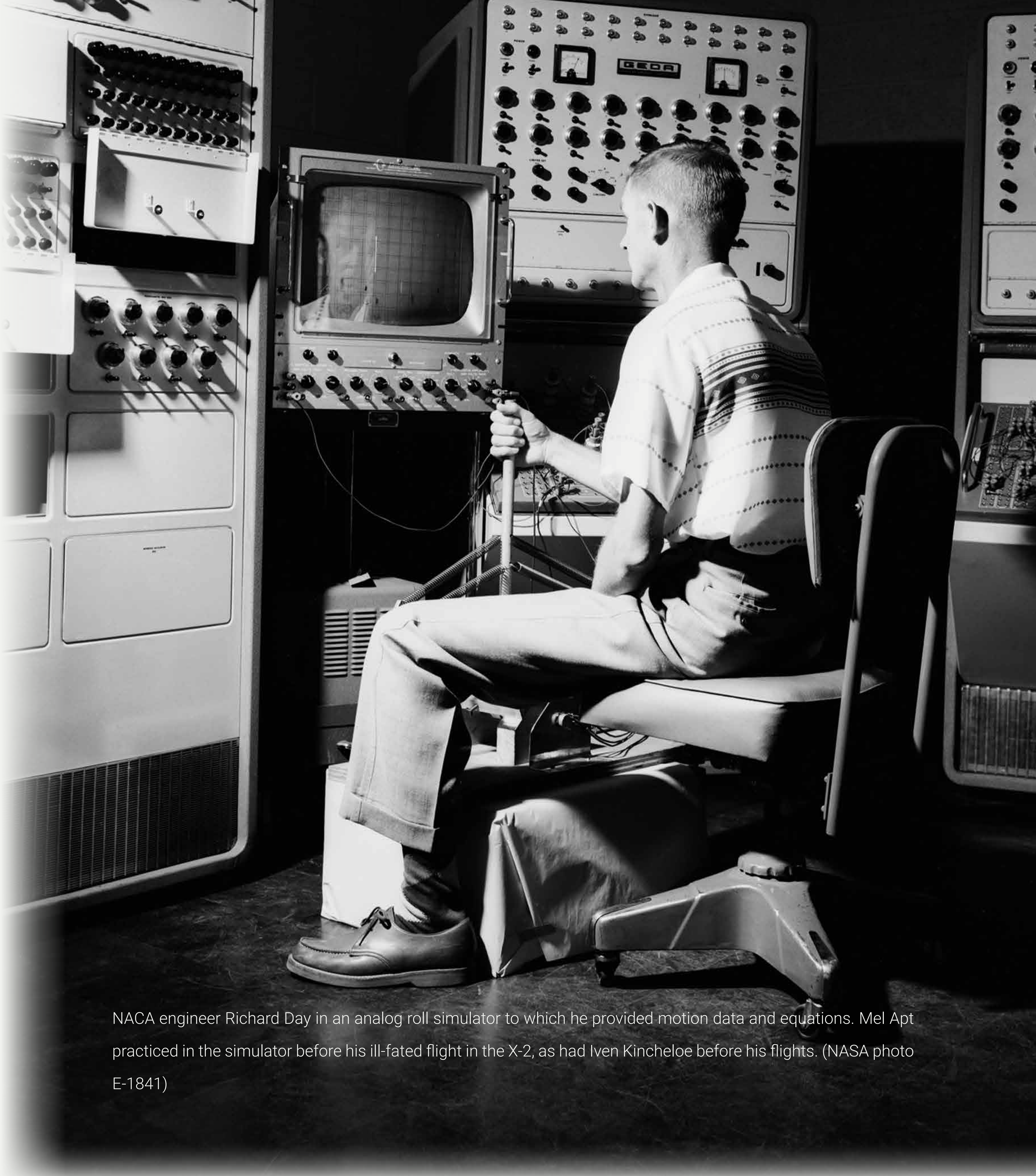
The Bell X-2

But on the X-2's next flight, tragedy struck. Following instructions—and flying his first rocket plane mission—Capt. Milburn G. Apt took the X-2 to a record speed of Mach 3.2, or approximately 2,094 miles per hour. As he turned back toward the base, however, Apt lost control of the plane and the X-2 entered a spin. The aircraft had been equipped with a jettisonable nose that was supposed to protect the pilot until he reached a speed slow enough for a normal bail-out. (The pilot was meant to remain in his seat, inside the separated front portion of the aircraft, until it was safe to use the parachute.) But while Apt jettisoned the nose successfully, he wasn't able to bail out before the cockpit section crashed into the desert.

The accident ended the X-2 program, although it did lead to several design improvements for future research aircraft. For one thing, the jettisonable nose concept was discarded in favor of an ejection seat. Researchers also suspected that one of the causes of Apt's accident was cockpit instrumentation that made him think he was going slower than he actually was, leading him to initiate a turn in the X-2 sooner than he should have. Consequently, future research aircraft were outfitted with more precise and accurate flight instruments.

Research aircraft were not the only planes pushing the boundaries of Mach 2 flight. While the Air Force and NACA were exploring ever higher and faster flight with the Douglas Skyrocket and the Bell X-2, the Lockheed Aircraft Corporation was putting a Mach 2 fighter plane into production – the F-104 Starfighter. The F-104, which flew for the first time in 1954, had a long, narrow fuselage and a tiny, straight, razor-thin wing only 4.2 inches thick at its root, leading some to refer to the fighter as *"a missile with a man in it."*

The Dryden team had requested – and received – an instrumented, pre-production model of the Starfighter for research in roll coupling and pitch-up phenomena. The Starfighter's configuration was similar to the X-3's, making it a logical test bed for researching some of the difficulties being encountered by many supersonic aircraft at the time. Lockheed was having problems with its F-104 test program, however, and by the beginning of 1957, Dryden's YF-104A was the only instrumented Starfighter still in existence.



NACA engineer Richard Day in an analog roll simulator to which he provided motion data and equations. Mel Apt practiced in the simulator before his ill-fated flight in the X-2, as had Iven Kincheloe before his flights. (NASA photo E-1841)

YF-104A

Air Force officials asked Dryden to return the plane so testing could be completed, but Dryden managers suggested instead that the center complete the F-104 testing for the Air Force and Lockheed, using Dryden's research pilots and instrumentation. Lockheed and Air Force program officials agreed, and a successful flight test program followed that led to several important changes in the Starfighter, including a yaw damper and new operational cautions in the pilot's operating handbook. The Mach 2 Starfighter still commanded respect from pilots who flew it, but the flight testing at Dryden helped make the plane a much more successful Air Force fighter.

The YF-104A also proved to be a valuable research platform for Dryden. After completing its initial test program, the aircraft was used for several other training and research efforts, including the training of X-15 pilots in the use of reaction controls. Even before the X-2 took to the skies, Dryden researchers were already beginning to explore two new frontiers that would prove even harder to conquer than the sound barrier: hypersonic flight and space.

Publicity photo of the Douglas X-3, staging preflight operations. (NASA photo ET68 0414)

The Dryden Flight Research Center may have been founded to support a single research effort, but within a few months of its inception, it had already committed to a wider range of research, establishing a tradition of project diversity and flexibility among its employees that continues to this day. From its first day in operation, Dryden also was an exercise in partnerships. The X-1 was a joint effort among Dryden, the Air Force, and Bell Aircraft. Likewise, the Douglas D-558-1 was the product of a team that included the U.S. Navy and the Douglas Aircraft Company as well as NACA/Dryden. There were tensions and issues to be resolved with each of those projects, but the teams worked out their differences and produced highly successful flight research efforts that improved and expanded the understanding of high-speed and high-altitude flight.

NACA pilot Bob Champine, with ground crew members making final preparations, before a research flight in the Douglas D-558-1 Skystreak. (NASA photo E-203)

Conclusion

That knowledge was quickly incorporated into production aircraft of the day, particularly in the high-speed fighters coming off the assembly lines with new engines, wings, and configurations. The research results produced through Dryden's efforts – not only with X-planes but sometimes through flight testing of new production aircraft – allowed this new generation of fighter planes to be safer and more effective in carrying out their missions. The research was not without risk, and a number of lives were lost in the process of the work conducted by Dryden, the Air Force, and the manufacturers exploring this unfamiliar realm of flight. But it was through that focused effort that all the parties involved learned about deadly hazards in the transonic and supersonic worlds, as well as about design flaws and fixes that saved the lives of countless pilots who followed in the footsteps of those first, brave explorers.

NATIONAL ADVISORY COMMITTEE
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HIGH-SPEED FLIGHT STATION

NACA personnel in front of their new building, August 12, 1954. The new facilities and the number of people shown here clearly demonstrate how much the organization that became the Dryden Flight Research Center had grown in less than a decade since Walt Williams and a handful of people had first arrived at the desert location to begin flight research on the XS-1. The rapid growth suggested the utility of their work for the nation's expanding aviation needs. (NASA photo E-33718, originally obtained courtesy of the Air Force Flight Test Center Historical Reference Collection)

By 1956, Dryden already was a place where employees from different research disciplines came together, often with outside partners, to meet the challenges of diverse research projects and aircraft. But the world was changing. A new frontier, and a new kind of race, was about to begin. It was a shift that would alter not only the focus of Dryden's work, but also the face and nature of the agency that had established Dryden in the first place. And meeting the challenges of this new race successfully would require the same levels of flexibility, creativity, and innovative spirit that had earlier allowed a small cadre of engineers technicians, pilots, and support personnel to take the X-1 beyond the sound barrier.

The sonic wall had been broken. Now, the new challenge and frontier was space.

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1 From Edmond C. Buckley to Hartley A. Soule´, letter, January 22, 1948, as quoted in Richard P. Hallion and Michael H. Gorn, On the Frontier: Experimental Flight at NASA Dryden (Smithsonian Books, Washington, D.C., 2003), 24.

2 HSFS, "10th Anniversary Supersonic Flight," X-Press (October 14, 1957), 3, as quoted in Hallion/Gorn, On the Frontier, 15.

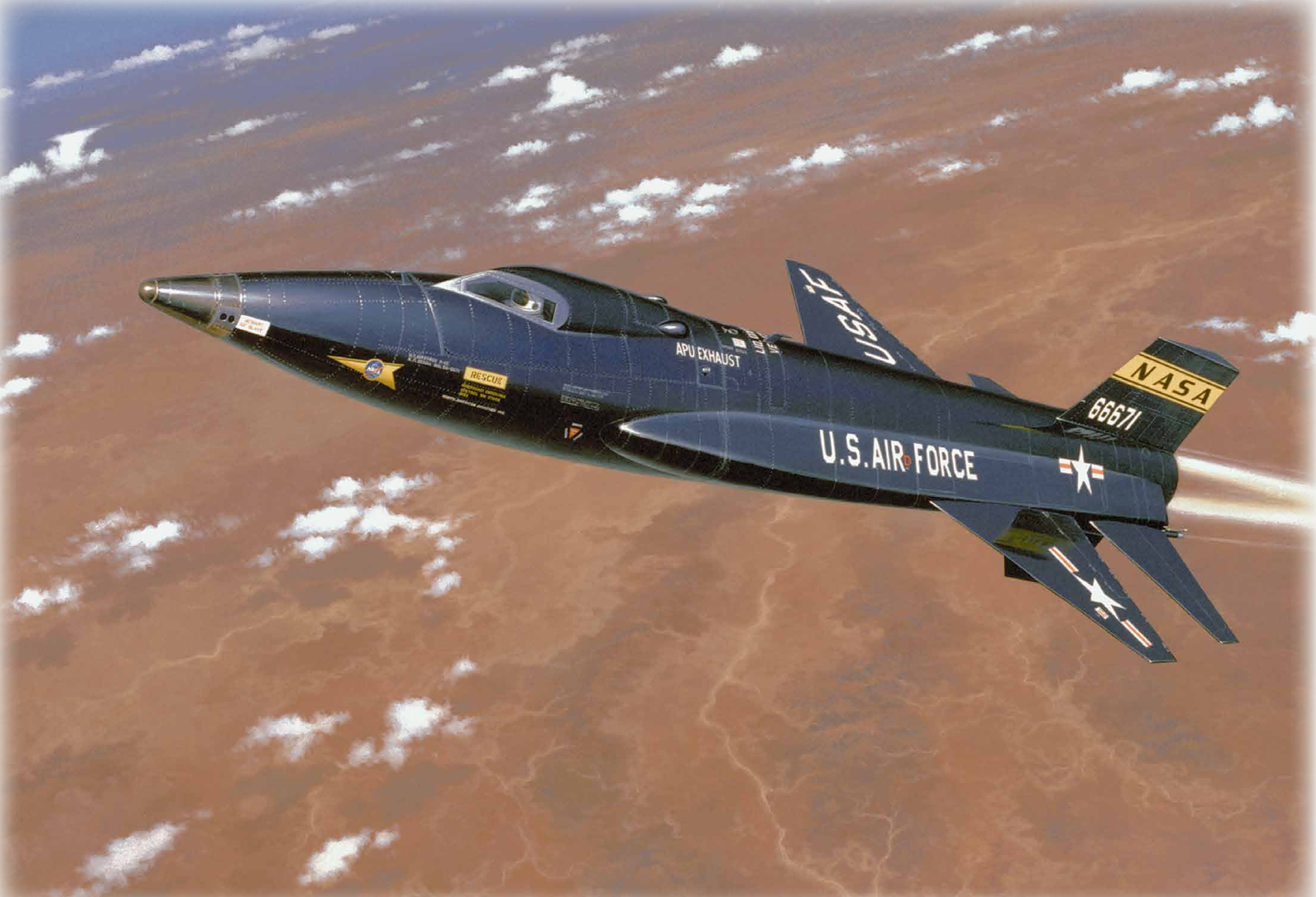
3 Hallion/Gorn, On the Frontier, 21.

4 Hallion/Gorn, On the Frontier, 21.

5 The U.S. Army Air Forces became the U.S. Air Force, a separate branch of the military, on September 18, 1947.

6 Hallion/Gorn, On the Frontier, 80.

7 Gen. James Doolittle, from an untitled document written in 1958, quoted in an untitled, undated transcript of a NASA presentation on the X-1 program; Richard P. Hallion files in the NASA Historical Reference Collection.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With or Without Wings

X-15

by Stan Stokes

With or without Wings

By the mid-1950s, Dryden had already widened its original focus to incorporate numerous types of aeronautical flight research, conducted with a variety of partners. The center and its relatively small workforce had also gotten used to managing multiple research efforts simultaneously, which added not only to the center's technical agility, but also to its ability to transfer the lessons of one research effort to the challenges of the next project down the line or down the hall.

The projects undertaken at Dryden in its first few years may have centered primarily on the challenges of high-speed aircraft configurations and flight. But that boundary began to dissolve before the center was even 10 years old. For soon after the skies had reverberated with the first boom of supersonic flight, researchers began looking toward a far more distant and challenging goal: flight outside the atmosphere itself.

Aerial view of the NACA High-Speed Flight Station on August 24, 1954, with the facilities in the middle of the photo and Rogers Dry Lake behind them. (NASA photo ET61 0141)

The X-15

As early as 1952, several prominent researchers began lobbying for a flight research vehicle that could be used to investigate some of the basic challenges human space flight would entail. Between 1952 and 1954, however, the NACA had its hands full with all of the supersonic research aircraft it was managing. So it was 1954 before serious attention was focused on developing a research vehicle that could reach the boundaries of space and the hypersonic speeds at which a spacecraft would fly.

Official design requirements for the vehicle, known as Project 1226 but eventually designated the X-15, called for an aircraft that could fly at speeds from Mach 4 to Mach 10 and at altitudes from 12 to 50 miles above the Earth. In December 1954, the NACA, the Air Force, and the Navy signed an agreement for the plane that gave the Air Force administrative control of its design and construction and the NACA responsibility for technical supervision. The partners shared responsibility for the program's cost.

In November 1955, North American Aviation won the contract for construction of three X-15s, which were to be capable of flying 6,600 feet per second – about six times the speed of the original X-1 – and reaching an altitude of 250,000 feet. Those numbers represented a staggering leap in performance over any existing aircraft – research or otherwise – of the day. The scientists and engineers at the NACA and North American believed that the X-15 design was based on sound principles, but they also knew that if they were to meet the program's ambitious deadlines, they couldn't wait to have all the remaining uncertainties and questions resolved before proceeding.

When the contract for the X-15 airframe was awarded, the technology for its 57,000-pound-thrust engine (representing 608,000 horsepower at 4,000 miles per hour) did not exist. A contract for the powerplant was awarded to Reaction Motors in September 1956, but the engine still wasn't available when the first X-15 airframe was delivered in 1958. In fact, Reaction Motors' XLR-99 engine wasn't ready for installation in the X-15 until 1960. So for the first two years of the program the X-15s flew with two XLR-11 rocket engines left over from the X-1 program.

The X-15

North American also was forging new ground with the X-15's airframe. The structure of the X-15 had to withstand forces up to 7 gs, and the friction generated by its high speed was expected to create temperatures on the airframe as high as 1,200 degrees Fahrenheit. That was beyond the tolerance of any aircraft material used up until that time, including steel. So North American built the X-15 out of a new, heat-resistant nickel alloy called Inconel X®. The X-15 incorporated other innovative systems, including rocket-powered reaction controls. It also was equipped with 1,300 pounds of instrumentation, including 1,100 sensors.

The challenges of the X-15 program stretched far beyond the building of the aircraft. The program's main research goals were to investigate aerodynamic forces; heating, stability, and control (including the use of reaction controls); reentry characteristics; and human physiology at extremely high speeds and altitudes. Accomplishing this research was particularly difficult for two reasons. First, it required flying the aircraft far beyond any condition or speed anyone had attempted before in a piloted vehicle. The potential for encountering dangerous, unknown difficulties and phenomena was huge. But the research goals also required operating the aircraft throughout an incredibly wide flight envelope. The X-15 was air-launched at approximately 45,000 feet and accelerated to between Mach 2 and Mach 6 while climbing as high as 350,000 feet. It then had to execute a successful hypersonic reentry through the Earth's atmosphere and glide back to a 200-mile-per-hour, unpowered landing on a dry lakebed.

Delivery ceremony for X-15 number 2, February 8, 1961. Left to right" North American test pilor (and former NACA research pilot) Scott Crossfield hands the keys over to fellow X-15 pilot, Air Force Maj. Robert White, while X-15 pilot and later astronaut Neil Armstrong looks on with his elbow on another X-15. White became the first pilot other than Crossfield to fly X-15 #2 on March 7, 1961. (NASA photo ET61 0088)

These requirements meant that the X-15's designers had a very tough task. Even something as ordinary as a control stick wasn't simple when it came to the X-15. To compensate for the wide variety of speeds and control forces the X-15's flight envelope entailed, North American ended up putting three control sticks in the cockpit. A conventional center stick was used at slower speeds and a right-hand stick was used for high-g maneuvering, when it was critical not to over-control the aircraft. A left-hand side stick was used to operate the reaction controls when the aircraft was outside the Earth's denser atmosphere, where little air remained to flow over the standard control surfaces.

The complexity of the X-15 program also presented new challenges in terms of ground and air support. The B-29 and B-50 launch planes were replaced by a B-52 with a special pylon for the X-15 mounted under one wing. Dryden also had to beef up its ground control facilities. Up until that point, the only control room Dryden used for monitoring its flight research projects was a portable van and radio. But the X-15 was far too demanding for such simple equipment. So Dryden built a formal control room to enable engineers to monitor and respond to the deluge of data the X-15 transmitted on every flight. That control room later served as one of the models for the Mission Control Room for the Mercury program at Cape Canaveral.

Tracking an aircraft traveling 6,600 feet per second was also a new challenge for both the NACA and the Air Force. A special flight corridor, known as the *"High Range,"* was established for the X-15 flights. It measured 485 miles long and 50 miles wide and stretched from Wendover, Utah, to Edwards Air Force Base. In addition, radar tracking and telemetry sites capable of receiving 600,000 pieces of information per minute were set up in facilities at Beatty and Ely, Nevada, as well as at Edwards, to provide continuous coverage of X-15 missions during its flight. The High Range was also structured to follow a string of dry lakes between the launch point and Edwards so the X-15 pilots would always have an emergency landing field within reach.

On top of all this were the maintenance and logistical burdens stemming from operating such a far-reaching, experimental rocket plane. It took ground crews the better part of a week just to complete the ground pre-flight check-out and preparation of all the X-15's complex systems and instrumentation. The night before a mission, crews and equipment had to be flown to each of the High Range tracking stations, while emergency personnel were stationed at key dry lake landing sites and a crew of 25 worked for hours to fuel and prepare the X-15 and its B-52 mothership for flight.

X-15 Simulator

All these efforts, however, were merely prelude to the tricky business of actually flying the hazardous rocket plane. Pilots and engineering crews had an analog X-15 simulator that they used for pilot training and flight planning, and the X-15 pilots spent many hours in the simulator before every flight. Nevertheless, aeromedical researchers discovered that the heart rates of X-15 pilots jumped from a normal rate of 70 to 80 beats per minute to a pulse rate of between 145 and 185 during the missions. The increase, which became a baseline health measurement for all future astronauts, was a byproduct and barometer of the keyed-up, highly focused psychological state that flying the X-15 required. The X-15 program was, without a doubt, one of the most challenging – and high-risk – research programs ever conducted at Dryden or anywhere else.

Even decades later, project engineers considered the X-15 to be in a league of its own in both scope and complexity. *"Everything it did was being done for the first time,"* one project engineer explained. *"We had problems in all areas every day, and every day it would be different. We'd get hit with totally unknown things because we were operating in an area we didn't understand. Fortunately, the airplane was overbuilt in all areas that allowed us to learn from our mistakes. We could heat cables and landing gear and crack windows... and it would still come home."*[1]

Or, at least it almost always came home. The nine-and-a-half-year, 199-flight program was a tremendously successful effort in terms of safety, especially given the difficulty of what researchers were attempting to achieve. But the program suffered four serious accidents. Two involved emergency landings at alternate lakebed sites when engine problems occurred after launch. North American test pilot Scott Crossfield escaped without injury when his still-fuel-heavy X-15 broke in two on touchdown, but Dryden pilot Jack McKay crushed four vertebrae when his X-15 rolled over during an emergency landing at Mud Lake, Nevada.

Less than a year after his first mishap, Crossfield was in the cockpit of an X-15 doing a ground test of its new XLR-99 rocket engine when an explosion occured. The 15-foot aircraft cockpit section that was left intact hurtled across the ramp and engulfed in flames. In a testament to the X-15's sturdy, heat-resistant, construction, Crossfield emerged from the cockpit unharmed as a crewmember sprayed a shower of water around him to keep the flames at bay.

An X-15 being launched from its NB-52B mothership, date unknown. (NASA headquarters photo X-15-1)

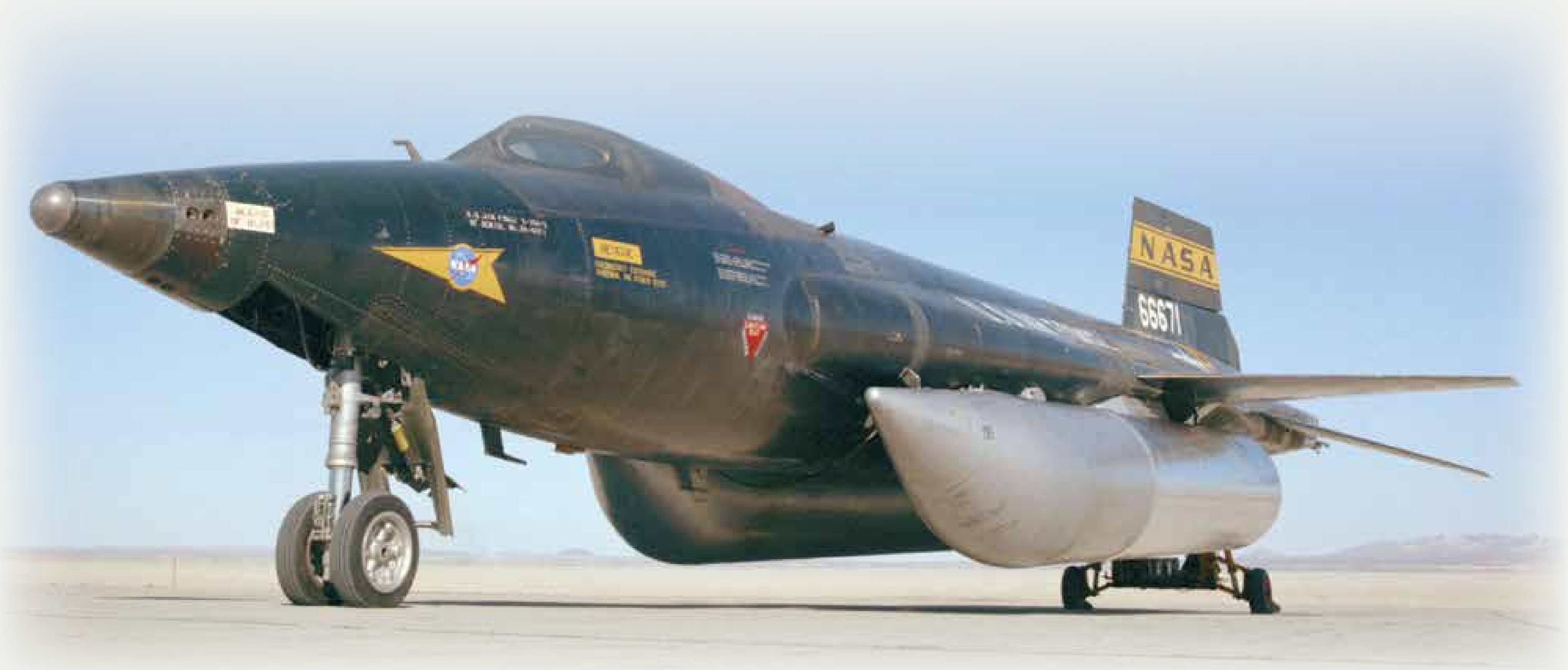
RESCUE
NORTH AMERICAN AVIATION, INC.
X-15
BEWARE OF BLAST

Research pilot Joe Walker, sitting in the cockpit of an X-15, shows the instrument panel and controls to the Mercury astronauts on September 14, 1959. Walker went on to set an unofficial world altitude record on August 22, 1963, climbing to 354,200 feet, the highest X-15 flight. (NASA photo E-4880)

Mach 5

Air Force pilot Mike Adams was not so fortunate. On a 1967 flight during which he reached Mach 5.2 and an altitude of 266,000 feet, Adams was distracted by a malfunctioning experiment and apparently misread a cockpit instrument, leading him to enter a sideslip as he approached reentry to Earth's atmosphere. Spatial disorientation suddenly compounded his problems, and at that speed and altitude there was little margin for error; the X-15 went out of control. In its ensuing gyrations, the X-15 broke apart and Adams was killed.

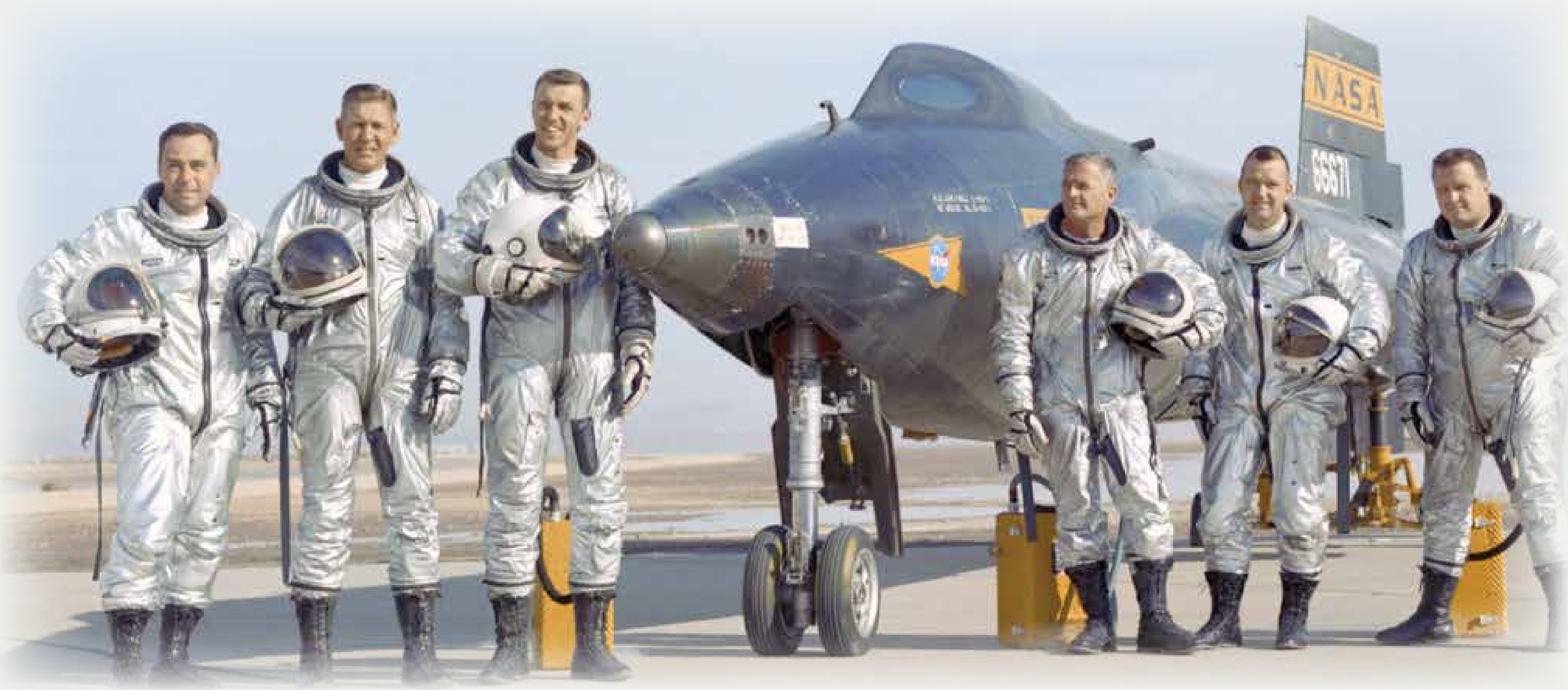
The accidents, however, could not overshadow the enormous achievements of the X-15 research effort. By any measure, the program was one of the most successful flight research endeavors ever conducted. It made more than two-dozen specific and significant contributions to future flight both within and outside Earth's atmosphere. In addition, the X-15 program generated more than 765 technical documents, greatly enhancing the nation's knowledge base on a wide range of aerospace topics related to high-speed atmospheric and space flight.



The X-15A-2 on the Flight Research Center ramp on October 8, 1965. This was a modified X-15 with a longer fuselage and two huge external propellant tanks beneath the wings. With an ablative coating, this version of the X-15 set a speed record of Mach 6.7 (4,520 miles per hour) with Air Force Maj. Pete Knight as the pilot. (NASA photo EC65 0899)

Perhaps the program's most important accomplishment was simply demonstrating that a high-performance, reusable vehicle could be successfully flown by a pilot outside Earth's atmosphere, brought back through reentry, and returned to a safe, unpowered landing. In the process, the X-15 also gave researchers a much clearer picture of the combined stress of aerodynamic loads and heating in a hypersonic, high-dynamic-pressure environment.

In addition, the X-15 led to the development of numerous technologies that benefited future space flight programs. The X-15 prompted the development of the first large, restartable, throttle-controlled rocket engine. The program also led to development of the first practical full-pressure suit for protecting pilots in space, as well as a high-speed ejection seat. The X-15 successfully tested a *"Q-ball"* (also called the Ball Nose) nose cone air data sensor, an inertial flight data system capable of functioning in an environment ranging from sea-level to near-space conditions, and the energy management techniques that astronauts would later use to land the space shuttle safely.



Six of the X-15 pilots next to the aircraft on December 2, 1965: (left to right) William J. "Pete" Knight, Bob Rushworth, Joe Engle, Milt Thompson, Bill Dana, and Jack McKay. (NASA photo EC65 1019)

The X-15 pilots also successfully demonstrated the use of reaction controls outside Earth's atmosphere. Reaction controls proved to be a critical technology not only for the X-15, but also for the Mercury capsule, the Apollo Lunar Module, and every other piloted vehicle ever flown in space. The Mercury capsule utilized a version of the X-15's complex controls, including its side-stick controller, on orbital missions. In addition, the X-15 tested a number of prototype systems that were subsequently used in the Apollo program. Among these was the insulation later incorporated into Saturn booster rockets, as well as horizon-measuring instrumentation that aided development of navigation equipment for the Apollo capsule.

In its later flights, the X-15 conducted a number of *"piggy-back"* research experiments that generated valuable results in other areas. The X-15 was outfitted with special instruments that measured sky brightness and atmospheric density, as well as wing-tip pods that collected micro-meteorites for further study. The X-15 program also ventured into the field of Earth-resources photography, a research tool that is invaluable today in helping track and determine the overall health of the planet.

DANGER
EJECTION SEAT
DANGER
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Left to right, NASA Flight Research Center Director Paul Bikle talking with NASA Deputy Administrator Hugh Dryden (for whom the center was later named) and Bickle's predecessor as head of the California research facility, Walter Williams. The three NASA leaders stand in front of an X-15 in April 1964. (NASA photo E-11146-47)

The exhaust plume from the X-15 rocket engine during flight in 1961. (National Geographic photo EC65 0885 by Dean Conger for NASA).

But one of the X-15 program's most significant contributions to the space program was no one technique, technology, or piece of hardware. It was simply the intangible and invaluable wealth of people and experience the program created. A number of the people at Dryden who had been involved with the X-15 program went on to assume key leadership positions in the space program, including Walt Williams, the center's first director, who went on to serve in several management positions, starting with Project Mercury. And Dryden research pilot Neil Armstrong, who had evaluated the use of reaction controls with both the F-104 and the X-15, went on to apply his expertise in the Apollo program, manually piloting Apollo 11's Lunar Module to the first moon landing in July 1969.

The Space Race

The X-15 program was, in many ways, a logical outgrowth of the early X-plane research into high-altitude and high-speed flight. But even as the X-15 program got underway, a rocket launch in the Soviet Union caused an upheaval in U.S. priorities, turning the nation's focus toward a simpler and quicker method of attaining orbit and entering space. The *"shot heard 'round the world"* was the launch of the Soviet satellite Sputnik on 4 October 1957 from a remote, secret installation in the Kazakhstan region of the U.S.S.R. The satellite weighed just 182 pounds, but its impact was greater than that of a megaton bomb. For the success of Sputnik meant that the Russians had beaten the U.S. into space. In addition to ensuing public embarrassment at being beaten to the punch by its Cold War enemy, the U.S. worried that Soviet space technology might give the Soviet Union a dangerous military advantage.

Famed rocket engineer and manager Wernher von Braun looks intently at the instrument panel of the rocket-powered X-15 while seated in the cockpit on November 30, 1963. Larry Barnett looks over his shoulder. (NASA photo E-7608)

15
NORTH AMERICAN AVIATIO
RESCUE

NASA pilot Joe Walker next to X-15 #2 after his flight on March 30, 1961, in which he achieved a speed of 2,760 miles per hour and an altitude of 169,900 feet. (NASA photo ET61 0111)

The threat had to be countered. The *"Space Race"* was on.

The first years of that race were not encouraging, from a U.S. perspective. The Soviets successfully sent a second Sputnik satellite into space within less than a month, while the first attempt by the U.S. to launch a Vanguard rocket, in early December 1957, ended in a spectacular and embarrassing explosion a mere two seconds after liftoff. Clearly, something drastic needed to be done to level the playing field. President Eisenhower asked for a national policy on space, and Congress began accelerating efforts to deal with the crisis. The result was the National Aeronautics and Space Act of 1958, which folded the existing National Advisory Committee for Aeronautics into a new and expanded agency: the National Aeronautics and Space Administration, or NASA.

Aeronautics was still considered an important area to support and explore, but starting in the early 1960s, the lion's share of the new agency's focus and funding was directed toward space. In many ways it had to be, especially after May 1961, when President John F. Kennedy committed the country to putting a man on the moon and returning him safely to Earth before the end of the decade. Accomplishing a goal that ambitious would require all the resources that NASA, industry, and the nation at large could throw at the problem.

NASA
U.S. AIR FORCE
NASA 9
NASA 9

The NB-52B number 003 flying a salute to X-15 #2, which it launched June 23, 1961, as the flight crew tends to the X-15. (NASA photo EC61 0034)v

The Parasev

The focus of Dryden's work was aeronautics. This would seemingly have relegated it outside the agency's new focus on space, making it an unlikely choice for related project work. But the flexibility for which the center had become known paid off again, and it was soon knee-deep in space program support projects. Dryden employees built and flew several dedicated research vehicles, and NASA officials quickly discovered that Dryden's fleet of research aircraft could be valuable tools for researching and flight-testing individual spacecraft components and concepts.

Although researchers at Dryden advocated a reentry vehicle that could fly back to an Earth landing after completing its mission in space, NASA decided to go with a simple, ballistic capsule for its first spacecraft. But even a ballistic capsule needed a way to land safely on Earth. In the early days of the space program, Dryden explored two potential systems for accomplishing that feat.

The Parasev in flight on February 5, 1962. (NASA photo EC63 0216)

Parasev (Paraglider Research Vehicle) 1A behind one of its tow aircraft, a Stearman biplane, on 24 August 1962. (NASA photo EC62 0146)

In 1959, Dryden's F-104s conducted a series of drop tests with the drogue parachutes designed to slow the Mercury space capsules before ocean splashdown. Over the course of multiple drops of the parachutes from above 45,000 feet, Dryden researchers discovered several critical design flaws in the chutes. These research flights enabled designers to correct the problems before the chutes were installed on the actual spacecraft, and the system operated reliably throughout the Mercury program.

As NASA looked toward the follow-on Gemini program, however, researchers began investigating other landing systems that might allow the newer, two-man capsules to be guided to a gentle touchdown on land rather than continuing with the more complex ocean splashdowns that a drogue chute system required. The leading candidate was something called a Parawing, an inflatable, steerable wing/parachute – not unlike the system incorporated into the X-38 Crew Return Vehicle almost 40 years later.

The M2-F1

In the spring of 1961, NASA gave North American Aviation a contract to build and test a prototype Rogallo Wing – named for its designer, Langley Research Center engineer Francis M. Rogallo – and Dryden was asked to support that test program. Several Dryden engineers thought it would be helpful to conduct research with a smaller vehicle before North American flew the full-size Rogallo Wing, and in December 1961 they were given permission to build a small paraglider for that purpose. The result was the Paresev I, a somewhat unsteady-looking vehicle that roughly resembled a hang glider attached to a three-wheeled dune buggy.

The unpowered Paresev was initially towed behind a ground vehicle, with the pilot controlling its movements by tilting its wing forward, aft, and side-to-side. That system was very squirrelly and unstable, and after the towed Paresev nosed over into the lakebed on one flight, engineers completely redesigned the wing and control system. The resulting Paresev I-A had greatly improved handling characteristics and, after initial ground-tow tests, was taken aloft first behind a Stearman biplane and then an L-19 Bird Dog observation plane. Eventually, the Paresev was equipped with the same type of inflatable wing North American was testing and dubbed the Paresev I-B. Over the course of two years, the Paresevs completed 100 ground tows and 60 air tows, and the aircraft eventually demonstrated acceptable handling characteristics. Unfortunately, North American's full-size Rogallo Wing test vehicle was less successful. In 1964, as costs and time delays increased, NASA dropped the Parawing program and research with the Paresevs ended.

But the importance of Dryden's Paresev research went beyond its contributions to the Gemini landing system. It also demonstrated Dryden's ability to conduct small-scale, innovative, and low-cost research, as well as the value of those initial experiments to larger and more costly research programs. As time went on, in fact, Dryden's ability to test individual components with the help of its highly instrumented fleet of research aircraft, as well as its ability to conduct innovative and small-scale research projects, became two of the center's trademark strengths.

The M2-F1

One of the best-known programs ever conducted at Dryden, in fact, grew out of just such a small-scale, innovative research initiative undertaken at the same time as the Paresev project. Its origins dated to the early 1950s, when NASA's Ames Research Center engineers began exploring hypersonic *"lifting reentry"* shapes. One in particular that showed promise was, in essence, a 13-degree cone, sliced in half longitudinally and with the edges rounded out a bit. The shape was dubbed a *"lifting body"* because it derived its lift from the rounded shape of its fuselage. By 1958, researchers at Ames had developed and refined the concept – on paper – into a vehicle called the M2. But the researchers still had questions about the vehicle's controllability, since indications were that it would be unstable at slower speeds and would require a very steep descent angle.

Clearly, the best way to answer those questions was to build a version of the vehicle and test it in flight. But NASA already had chosen a ballistic capsule instead of a lifting reentry vehicle for the budding space program, so there was limited support or resources for another lifting reentry project. It was against this backdrop that Dryden began its innovative lifting body research in an effort that exemplified the independent, innovative, pragmatic, and pioneer mindset of Dryden's technicians and engineers.

The lifting body program at Dryden began primarily through the efforts of a curious and innovative engineer and model-builder named R. Dale Reed. Reed had read about the preliminary lifting body research done at Ames, and he began building models of the M2 to test the concept for himself. He built a lightweight, free-flying model of the M2 that he launched repeatedly into the tall grass near his home and down the hallways of Dryden, modifying its control and balance characteristics as he progressed. He then attached the model to a remotely controlled mothership that could drop it from a slightly higher altitude. Pleased with the result, he had his wife film some of its flights with their 8mm home camera, using the film to lobby Dryden's management for permission to build a larger test model.

Fortunately for Reed, Dryden's director at the time, Paul Bikle, was a particularly independent-thinking and courageous manager. Bikle understood the value of innovation and encouraged that trait at the center, even if some research efforts his engineers wanted to pursue were slightly unconventional. There were no funds available from NASA Headquarters for testing the M2, but Reed – knowing that Bikle had control over a small *"director's discretionary fund"*– proposed a low-cost, home-built effort that drew on the passion and talent for aircraft building that existed at Dryden.

Wright's Bicycle Shop

Officially, the request was for permission and money to build a full-scale wind-tunnel model of the M2. In granting that funding and permission, however, Bikle noted that if the aircraft just happened to be built so that it was capable of actual flight...well, that would be something beyond management's control. Bikle evidently knew what his engineers really wanted to accomplish, and he supported the idea and their enthusiasm enough to conveniently look the other way while they set about doing it.

Reed pulled together a team from the pool of talented engineers, machinists, and welders at Dryden who worked on homebuilt aircraft projects in their spare time. The group strung canvas to isolate a corner of a hangar, hung a sign over it saying *"Wright's Bicycle Shop,"* and used the area to begin work on the M2-F1 aircraft. They designed and built a steel-tube frame, and drew up plans for a body that would be flat on top with a rounded nose and belly and two vertical fins at the back to give it directional stability and control. Constructing the lightweight fuselage shell was more problematic, but Bikle, who was a world-record-holding sailplane pilot, knew a sailplane builder at nearby Lake El Mirage who, he thought, could make the shell out of plywood. He allocated $10,000 from his discretionary fund for a fuselage shell contract and also sent one of his NASA craftsmen – who had worked on the building of Howard Hughes' mammoth *"Spruce Goose"* wooden flying boat – to help with the shell construction.

Aircraft in Dryden's hangar 4802. On the right are the three X-15s, including X-15A-2 which wears its light-colored ablative coating. Beyond that are a T-33 and two F-104s, which served as chase aircraft. On the left are the HL-10, the M2-F1, the F-5D, an F-4 Phantom, and the center's R4D utility aircraft. (NASA photo E-16993)

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Flying Bathtub

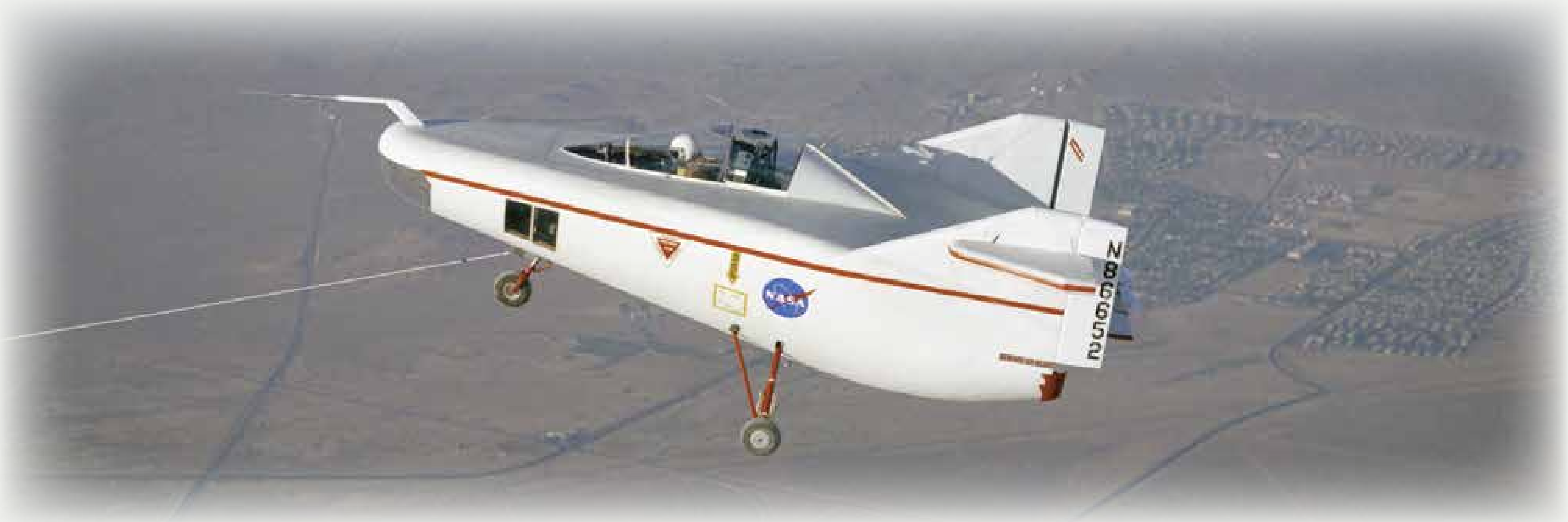
While the aircraft was being built, the team scouted around for a tow vehicle that would allow them to try some taxi tests with the M2-F1 before taking it to Ames for wind tunnel testing. Fortunately, one of the project's volunteers, a man named Walter *"Whitey"* Whiteside, was active in the local hot-rod racing circuit. Whiteside supervised the purchase of a 1963 Pontiac Catalina convertible and sent the car to Bill Straup's hot-rod shop in Los Angeles for modification, and then Mickey Thompson's shop for wheels and tires. The car arrived at Edwards capable of pulling the 1,000-pound M2-F1 faster than 100 miles per hour – which was just fast enough to get the aircraft airborne. The group also arranged, in typical creative and irreverent fashion, to have the car painted with a NASA logo on the side.

The group's initial plan was just to conduct ground tests of the M2-F1. But when he sat in the fully operational cockpit, NASA research pilot Milt Thompson suggested that perhaps it wouldn't really be flying if he just lifted the vehicle off the lakebed a few inches while he was being towed. Bikle gave Thompson tacit approval for the maneuver, but also cautioned the group to be careful. After some changes to the M2-F1's control system, the Pontiac successfully towed the plywood vehicle, dubbed the *"flying bathtub"* because of its bulbous shape, to an altitude of 20 feet, at which point Thompson released the towline and glided back to the lakebed.

NASA aerospace engineer Dale Reed in 1967 with model of the M2-F1 Lifting Body and the actual M2-F1 in the background. (NASA photo E-16475)

Paul F. Bikle, Director of the NASA Flight Research Center from September 15, 1959, to April 27, 1979. This photo was taken on September 16, 1959, the day after Bikle became Center Director. (NASA photo E-4875)

Once the M2-F1 was returned to Dryden from its wind tunnel research at Ames, Reed and the rest of the group went to Bikle for permission to actually fly the aircraft. NASA Headquarters had not sanctioned the project, and Dryden's director of research engineering went on record opposing any flight testing other than towing a few inches off the ground because he felt the information they stood to gain was not worth the risk to Thompson. But Bikle thought differently. Fully aware that he was putting his NASA career on the line, Bikle authorized the flights. Over the course of Dryden's history, the willingness of its managers to back innovative solutions and creative projects contributed every bit as much to the center's success as the individual skill of any pilot, engineer, or technician.



The M2-F1 in flight. (NASA photo EC63 0226)

Lunar Landing

On 16 August 1963, the M2-F1 team towed the stubby aircraft to 12,000 feet behind the center's R4D (the Navy's version of the DC-3). After release from the tow plane Thompson brought the glider back to a safe lakebed landing, inaugurating Dryden's lifting body research program. The entire M2-F1 project had cost only $30,000.

The M2-F1 went on to complete 77 research flights (and some 400 tows by the Pontiac) and be flown by 10 NASA and Air Force pilots. There were no major mishaps in the program, but the pilots quickly discovered that the M2-F1 had a nasty tendency to develop a pilot-induced roll oscillation. On two occasions the oscillation became so severe that the M2-F1 ended up inverted behind the R4D while still attached to the towline. Despite calls for him to eject, the pilot coolly released the towline and managed to turn the maneuver into something approximating a barrel roll, touching down on the lakebed at the bottom of the roll.

Eventually, the M2-F1's flight characteristics led Bikle to ground the aircraft. But the plywood vehicle's flights proved the worth of exploring the lifting body concept. When the M2-F1 first flew, only a few people at NASA Headquarters were even aware of the project. NASA's administrator discovered that the aircraft had flown only when, during testimony before a committee on Capitol Hill, a congressman who had read about the event in a newspaper asked about it. By the time Bikle grounded the M2-F1, however, Headquarters had authorized the building of two *"heavyweight"* lifting body vehicles for further flight research. That lifting body research continued at Dryden for almost a decade, generating invaluable knowledge and understanding of lifting reentry spacecraft that designers twenty years later would turn to for more cost-effective solutions to the challenge of leaving the planet and returning safely home again.

The Lunar Landing Research Vehicles

In the early 1960s, however, the challenges facing researchers involved not only taking off from the surface of our own planet, but also landing safely on the surface of another celestial body. Landing on the moon presented many difficulties, including the fact that the moon's airless environment would render aerodynamic flight controls useless. Consequently, the Lunar Module (LM), as the landing vehicle was designated, would have to be controlled entirely by its propulsion systems.

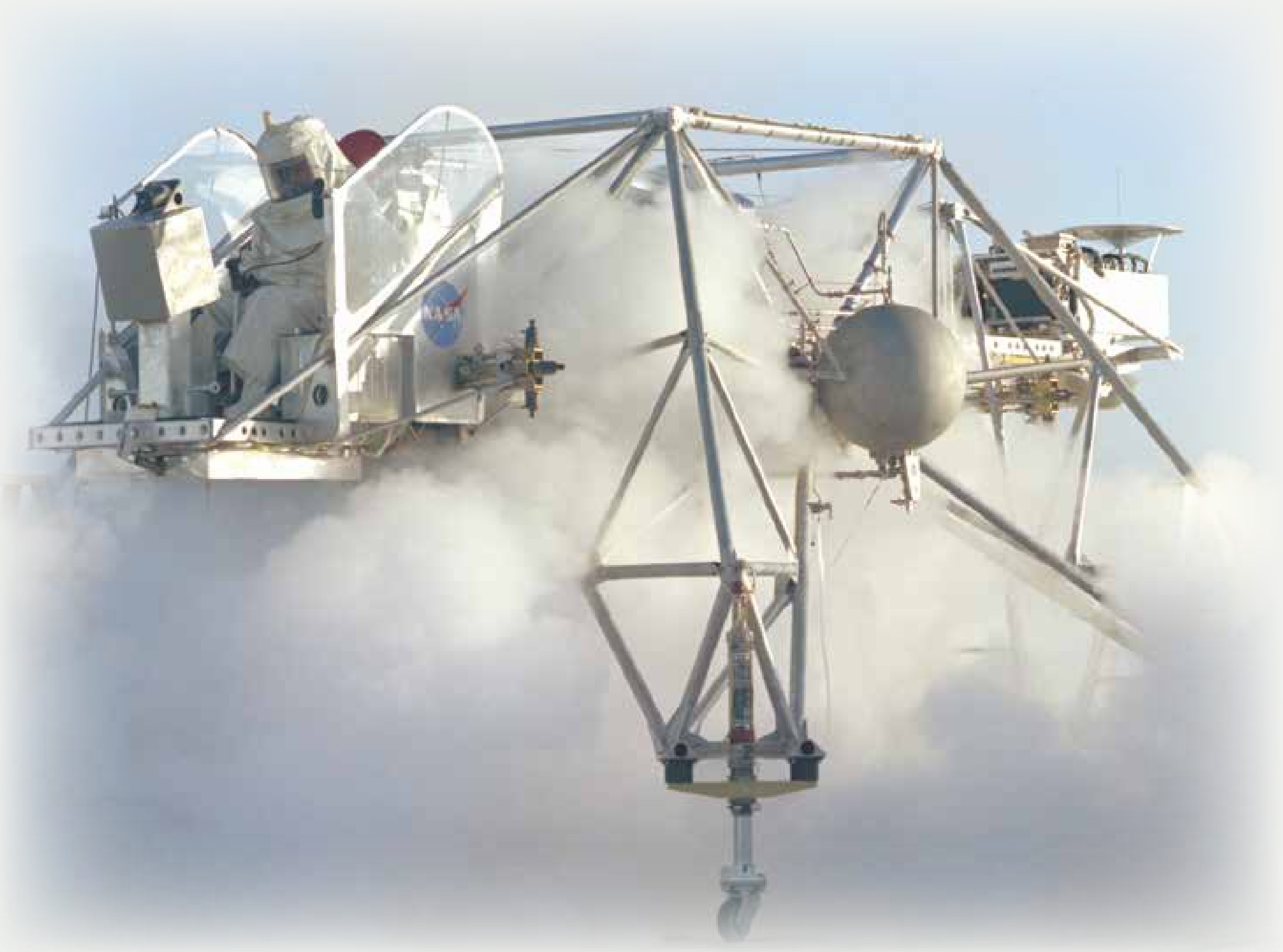
From left to right, Warren Wilson, Gene Matranga, Dale Reed, and Milt Thompson are gathered around models of the X-15, the Lunar Landing Research Vehicle and the M2-F1 Lifting Body on November 28, 1963. (NASA photo E-10675)

The Grumman Aircraft Corporation was given the contract to build the actual LM, but NASA managers didn't want the astronauts' first attempt at flying such an unusual vehicle to be on the moon, where they would have but one chance to get it right. Clearly, a simulator was needed to train the astronauts ahead of time. NASA planned to build a fixed-base simulator, but that alone wouldn't give the astronauts a realistic feel for the lander's flight characteristics. Another kind of simulator was needed as well. At the Langley Research Center, engineers were exploring the concept of a simulator tethered to a large gantry. But researchers at Dryden, fierce advocates of the unique benefits of actual flight, argued for a free-flying test vehicle instead. Indeed, some engineers at the center had already begun working on a design for such a vehicle. They found a serendipitous ally in Bell Aerosystems Corporation, which had become a major helicopter manufacturer and a pioneering company in the field of vertical takeoff and landing (VTOL) aircraft research. Unbeknownst to the engineers at Dryden, Bell had also been working on a proposal for a free-flying lunar landing simulator. Working together, engineers at Dryden and Bell got approval to begin formal design work on a Lunar Landing Research Vehicle (LLRV) in December 1961. Just over a year later, Bell was awarded a contract to build two of the vehicles.

Lunar Landing Research Vehicle

To simulate the moon's gravity, which is only one-sixth that of Earth's, the LLRVs had a central vertically mounted jet engine sitting in a double gimbal, ensuring that the engine remained perpendicular to the ground regardless of the vehicle's attitude. The LLRVs also had a cluster of large thrusters for climb and descent when in lunar simulation mode, and 16 smaller thrusters that the pilot used to control pitch, yaw, and roll. In addition, the vehicle was equipped with emergency thrusters to be used if the main jet engine malfunctioned. The vehicle was equipped with a zero-zero ejection seat. When in lunar simulation mode three analog computers maintained just enough engine thrust to negate five-sixths of Earth's gravity and maneuvered the jet automatically to counter side forces of wind gusts, all to create as genuine a feel as possible for flight in the lunar environment.

The resulting vehicles were arguably the strangest-looking research aircraft ever flown at Dryden, looking something like a cross between a child's jungle gym and a science fiction contraption. But they provided a remarkably effective method for investigating flight and propulsion controls, pilot displays, visibility, and flight dynamics associated with the LM, as well as giving astronauts experience in operating that kind of landing craft.



A Lunar Landing Research Vehicle undergoing pre-flight servicing prior to its first flight on October 30, 1964. The "pilot" wears protection against the nearly pure hydrogen peroxide droplets. (NASA photo EC64 0447)

The first LLRV made its maiden flight on October 30, 1964 and over the next two years NASA pilots made 204 fvlights in the vehicles, incorporating modifications along the way to make the LLRVs more like the real LM. In early 1967 the first LLRV was shipped to NASA's Manned Spacecraft Center (MSC) in Houston, where NASA redesignated it a Lunar Landing Training Vehicle (LLTV) and put it, along with three other LLTVs ordered from Bell, to work training the Apollo astronauts.

Mercury astronaut Virgil "Gus" Grissom and Milton O. "Milt" Thompson stand in front of the Parasev. Both flew the research aircraft (NASA photo E-8937)

All of the lunar mission commanders and their backup pilots flew the LLTVs before their space flights, and all of them considered those experiences extremely valuable. The training flights were not without risk or difficulty, however. Three of the four LLTVs crashed in the course of their use, though all the pilots ejected safely. The first pilot who had to eject, in fact, was Neil Armstrong. Despite that incident, in later years Armstrong recounted that when he undertook the first lunar landing he found himself extremely grateful for the experience he gained in the LLTV. As Apollo 11's *"Eagle"* LM descended toward that historic first lunar landing, Armstrong realized that the craft was heading for a wholly undesirable vtouchdown spot. So although the LM was equipped with an automatic landing system, Armstrong took over and flew the craft manually for the final 30-40 seconds of its descent, guiding it to a safer, more suitable site. Armstrong later said that it was his experience flying the LLTV that gave him the confidence to take over from the automatic system.[2]

Conclusion

Once again, Dryden's belief in the necessity and value of flight research, the innovative thinking of the engineers who worked there, and the ability of those engineers to work with other partners as part of a creative team had proven a winning combination – even with a problem as seemingly far from the field of aeronautics as landing on the moon.

Conclusion

The Dryden Flight Research Center may have been founded to research high-speed flight within our own atmosphere, but as NASA and the nation's focus and needs changed, the center showed remarkable versatility in tackling problems and projects in a wide variety of disciplines. Of course, adaptability and creative innovation had been required talents for Dryden employees since their first days at the Muroc Army Air Field. The center's flexibility also was aided by its relatively short past and its long distance from NASA Headquarters in Washington, D.C. The lack of a rigid, long-established bureaucracy or entrenched procedures at Dryden, as well as its small staff and isolated location, made it easier for researchers there to pursue *"outside-the-box"* ideas and thinking.

Each change in research direction required adjustment by the Dryden staff, and some adapted better than others. But for the most part, those who chose to work at Dryden shared a passion for invention, exploration, and flight. The particular vehicle used for that exploration might change, but the challenge of figuring out propulsion, flight controls, structures, and aerodynamics to make a vehicle fly – inside or outside Earth's atmosphere – remained a constant. There was always a better way to combine those elements to gain capability, efficiency, or some other improvement. And with technology changing all the time, the possibilities were virtually endless.

Not everyone shared this understanding, however. As Dryden approached the end of its second decade of research, it looked as if there might not be a third. As the X-15 program and the preparations for Apollo wound down, the U.S. House of Representatives Committee on Science and Astronautics recommended that Dryden be closed, as *"no further activity beyond the X-15 would require the existence of the center."*[3] Fortunately, the Senate Committee on Aeronautical and Space Sciences subsequently restored funding for Dryden – primarily on the grounds that the center would be needed for a new national effort in high-speed flight that was just beginning to appear on the horizon. That new effort was a program called the Supersonic Transport, or SST.[4]

Once again, the boundaries and priorities were shifting. And the next decade would take Dryden not only back into the world of high-speed atmospheric flight but into a new area of technology that would, in time, revolutionize aircraft design and operations. For the Apollo program launched more than just the era of extra-orbital space travel. It also ushered in the era of computer-aided flight.

RESCUE
NORTH AMERICAN AVIATION, INC.
X-15

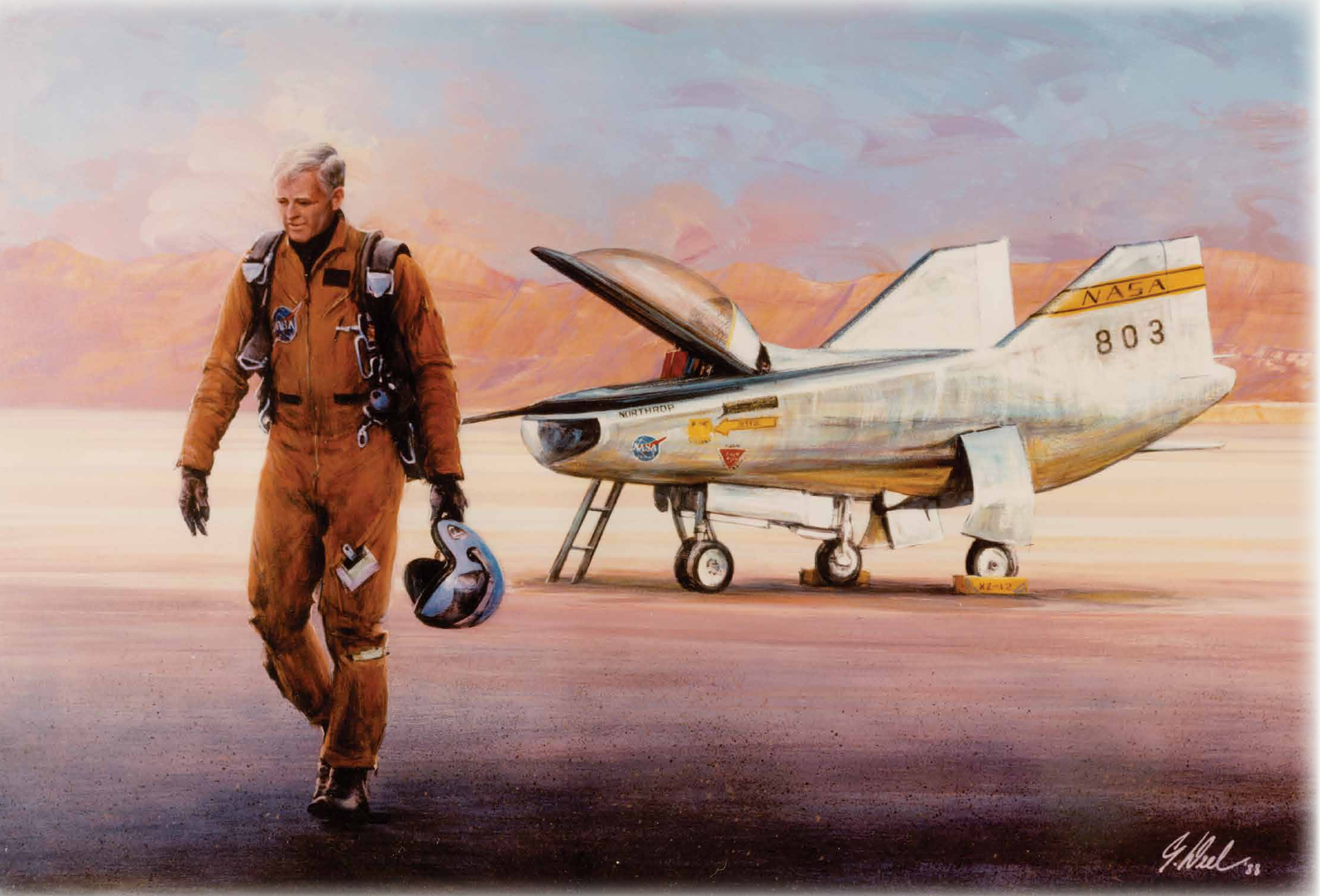
Research pilot Joe Walker, sitting in the cockpit of an X-15, shows the instrument panel and controls to the Mercury astronauts on September 14, 1959. Walker went on to set an unofficial world altitude record on August 22, 1963, climbing to 354,200 feet, the highest X-15 flight. (NASA photo E-4880)

1 Jack Kolf, interview with author, Palmdale, California, August 22, 1995.

2 Neil Armstrong, from a talk given to Dryden staff members soon after the Apollo 11 mission, as quoted in Robert Baron interview with author, Edwards, CA, August 4, 1995

3 Summary report of the House of Representatives Committee on Science and Astronautics recommendations affecting NASA for FYs 1964, 1965, and 1966. May 25, 1966, from Richard P. Hallion files in the Dryden Flight Research Center Historical Reference Collection, Edwards, CA.

4 Richard P. Hallion, On the Frontier: Flight Research at Dryden, 1946-1981 (Washington, D.C.: NASA SP-4303, 1984), 134.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Chapter 4

A Systems Revolution

First Lifting Body Flight

by Guy Deel

The "ironbird" enabled systems to be integrated and tested before flying on a research aircraft. The ironbird sits in the Research Aircraft Integration Facility (RAIF) (NASA photo EC02 0218-12)

Lifting Bodies

As the Dryden Flight Research Center entered its third decade the nation's focus may have been on the nascent Apollo program, but aerospace researchers were looking beyond the moon race. Dryden expanded its efforts with lifting body reentry spacecraft designs, which the center's researchers believed would offer NASA a superior and cost-effective option for achieving orbital flight in the post-Apollo era. It also was becoming evident that spaceflight was not the only arena in which the U.S. needed to expend greater effort to keep pace with the Soviets. U.S. fighter pilots in Vietnam were not faring nearly as well against newer, Soviet-designed fighters as they had in Korea, and the Soviet and European aerospace industries were developing supersonic transport technology that posed a potential threat to U.S. dominance of the civilian aircraft market.

Both the General Aviation (GA) and the air transport (airliner) aircraft industries were booming in the mid 1960s. But as more small aircraft took to the skies, a high number of stall-spin accidents led to questions about the safety of some GA aircraft designs. In addition, the expanded presence of large jet airliners created new safety concerns about how well the large and small aircraft would mix at airports.

As a result, Dryden found itself conducting research across a particularly broad spectrum in the mid and late 1960s – from aircraft flying 100 mph close to the ground to aircraft flying Mach 6 and beyond in the upper reaches of the atmosphere.

The Lifting Bodies

Based on the success of Dryden's "homebuilt" M2-F1 lifting body vehicle, in 1964 NASA authorized the construction of two "heavyweight" lifting body aircraft for further research. One was a metal version of the M2-F1, designated the M2-F2, and the other was a design developed at the Langley Research Center known as the HL-10. Both vehicles were built by the Northrop Corporation and equipped with an XLR-11 rocket engine to allow pilots to explore the characteristics and performance of the vehicles at transonic and supersonic speeds. The designs also incorporated small hydrogen peroxide rockets that could be fired by the pilot to slow the vehicle's descent, if necessary, on touchdown. The flight research program was to be run jointly by Dryden and the Air Force Flight Test Center at Edwards.

Heavyweight Lifting Body

The heavyweight lifting body flights began in July 1966 and were air-launched from the same B-52 used to drop the X-15s. In their first configurations, however, the lifting bodies did not handle very well. During its maiden flight, the HL-10's stability was so marginal that NASA instantly grounded the vehicle and sent it back to Northrop for modifications. The M2-F2, on the other hand, had the same poor lateral-directional stability as its lightweight predecessor, which eventually led to the program's only serious accident.

On May 10, 1967, NASA pilot Bruce Peterson was bringing the M2-F2 down to a lakebed landing when the vehicle began a series of violent, oscillating rolls. By the time he'd recovered control of the M2-F2, Peterson was heading for an unmarked area of the lakebed. (The runways on the lakebed were defined with dark, wide lines. Without these markings defining the runway against the sun-bleached monochromatic tan of the lakebeds it was difficult for pilots to tell exactly how far off the ground they were.) As he was trying to dampen the rolling motion, a rescue helicopter appeared in front of him, adding another distraction at a critical time.

The heavyweight lifting body M2-F3 flies on August 9, 1971. (NASA photo EC71 2775)

Research pilot Milton O. "Milt" Thompson walking away from the M2-F2 following a ground test. (NASA photo EC66 1424)

Realizing he was very low, Peterson fired the M2-F2's rockets to reduce his rate of descent and enable him to extend his landing gear, but it was too late. Before the gear could lock, he hit the lakebed. The gear sheared off and the M2-F2 cartwheeled across the hard lakebed at more than 250 miles per hour. Footage of the accident eventually became the opening sequence of the television series The Six Million Dollar Man. Amazingly, Peterson survived the crash, although he lost an eye from infection during recovery.

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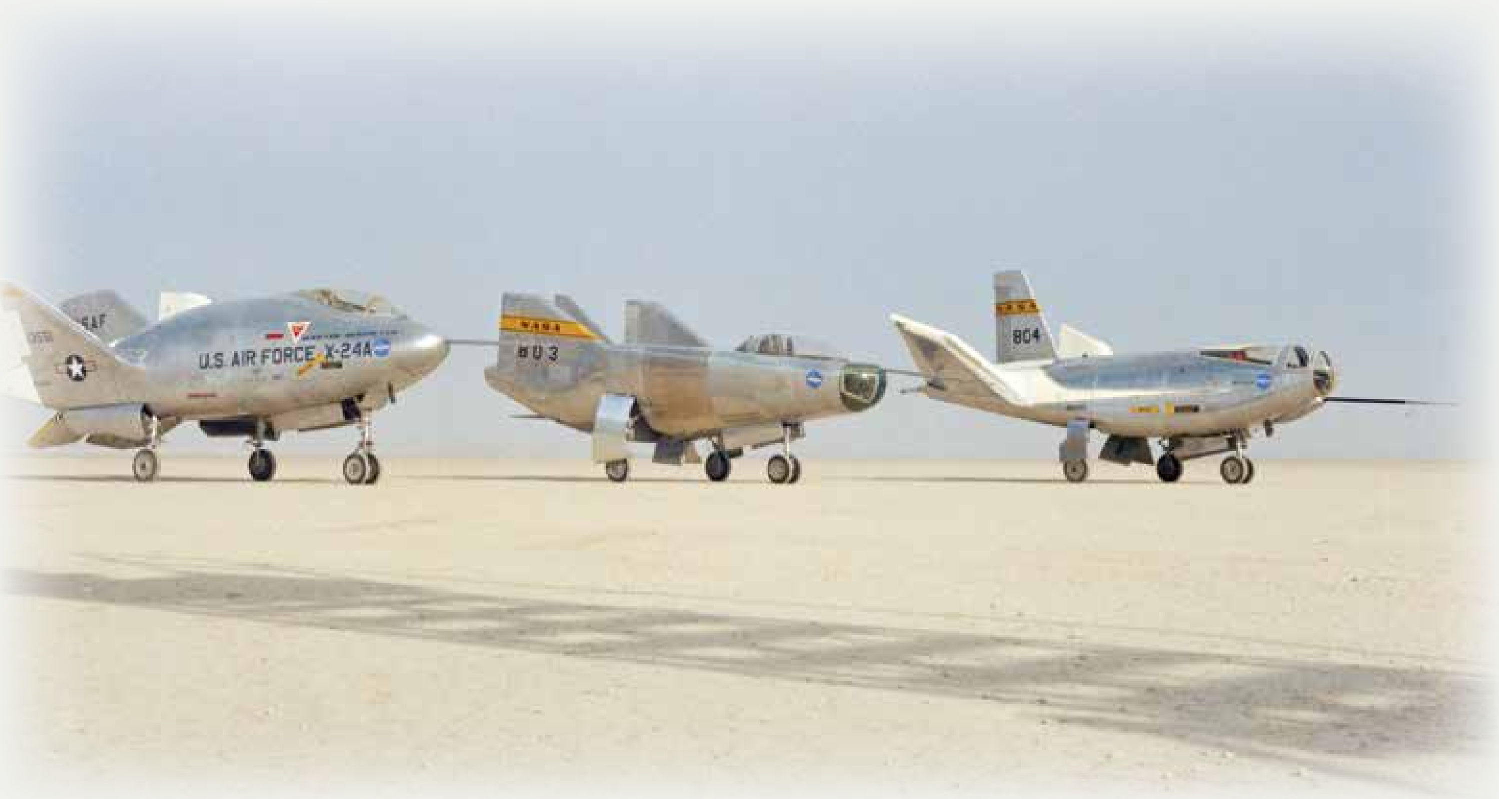
The Flight Research Center's Piper PA-30 Twin Commanche in flight on October 8, 1971. Among other things, this aircraft was used for general aviation studies. (NASA photo EC71 2846)

The X-24B

Peterson's accident was actually the fourth time the M2-F2 had demonstrated a severe rolling oscillation, and the modified HL-10 looked like it was going to have much better flying characteristics, so there wasn't a lot of support among NASA's managers for rebuilding the M2-F2. But a small group of researchers set out to change that situation. A team at the Ames Research Center determined, through wind tunnel tests, that adding a third fin between the M2-F2's existing tail fins would correct the problem. A couple of champions for the program wrested small amounts of money from NASA Headquarters for modification to and rebuilding of the aircraft. Northrop did the major work and delivered a "*kit*" for the redesigned M2-F2, now named the M2-F3, to Dryden for final assembly. Three years after Peterson's accident, the redesigned and rebuilt vehicle returned to the skies.

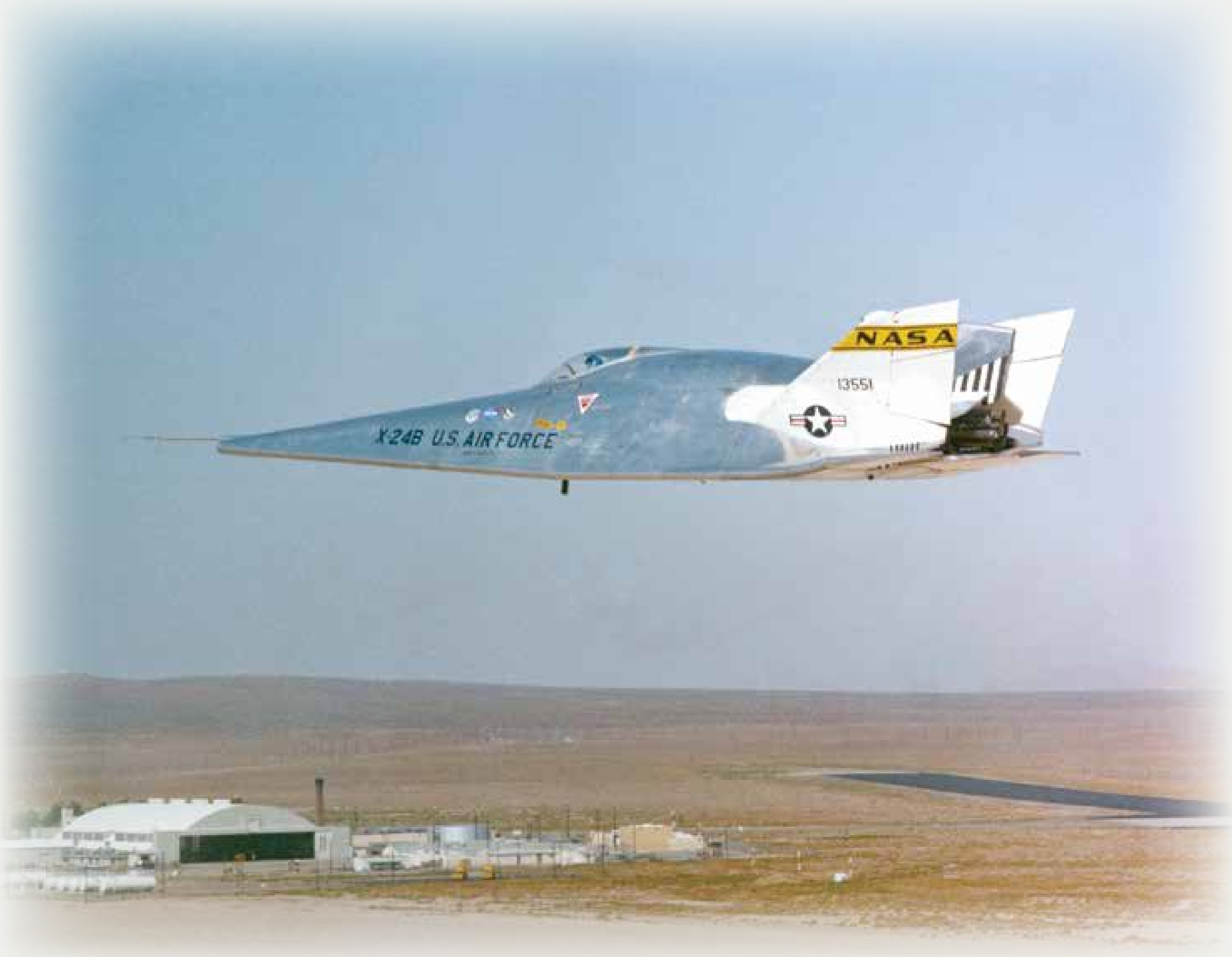
The lifting body flight research program eventually added two other Air Force-sponsored configurations: the Martin-Marietta X-24A, and its derivative, the X-24B. The X-24B, which was literally built around the existing fuselage of the X-24A, was by far the sleekest and highest performing of the lifting body designs. It had a higher lift-to-drag ratio than the rounder models, which allowed it to glide for a much longer distance. Air Force interest in the X-24B design was driven partly by a desire for a near-space-capable reconnaissance craft that could take pictures over the Soviet Union and still have enough gliding performance to make it back to the U.S. for landing. Although an operational vehicle never materialized, the X-24B proved a successful lifting body design with good handling characteristics.



Left to right, are the heavyweight lifting bodies including the X-24A, M2-F3, and HL-10, on Rogers Dry Lake, December 18, 1969. (NASA photo EC69 2353)

Advocates of the lifting body research hoped that one of the designs would be selected for NASA's emerging space shuttle program. It wasn't, primarily because of military requirements for a large, rectangular cargo bay, but the lifting body flights still contributed significantly to the shuttle program. Most important, they helped to demonstrate that a horizontal-landing spacecraft configuration with a very low lift-to-drag ratio could be landed successfully and accurately without propulsion. The initial Rockwell design for the shuttle called for air-breathing jet engines to power it to landing, in addition to rocket engines needed for launch. But the Dryden lifting body research helped convince shuttle managers that the orbiter could be landed safely as a glider, reducing its weight and increasing its payload capacity.

Five years later, mission planners still were debating whether the shuttle could be landed within the confines of a runway. To demonstrate that it could be, NASA pilot John Manke and Air Force pilot Mike Love performed a series of spot landings on the Edwards concrete runway with the X-24B, touching down precisely where they were supposed to land. The debate came to an end.



The X-24B lifting body flies on August 17, 1973. (NASA photo EC73 3744)

Unpowered Landing

The other contribution lifting body research made to the shuttle program was in demonstrating not only the fact that an unpowered landing could be done, but also how it could be done. Techniques developed by lifting body pilots, involving steep descent angles to maintain high speed throughout the approach that could then be transferred into energy for a flare and gentle touchdown, are the same as those used by space shuttle pilots.

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LAST ROCKET FLIGHT

Research pilot Bill Dana stands next to the X-24B lifting body after its last flight on September 23, 1975, (also the last flight of a rocket-powered aircraft at the Flight Research Center). (NASA photo EC75 4831)

The final shuttle design derived neither from an X-15 nor a lifting body, but it incorporated knowledge learned from both research programs. The sleek and swift X-15 and the stubby-looking *"flying bathtubs"* may have shared little in appearance. But between the two they demonstrated that it was possible to fly a high-performance lifting- body re-entry vehicle into space and bring it back, unpowered, to a runway landing here on Earth.

The lifting body program officially came to an end in 1975. Yet like a phoenix rising from the ashes, the concept has reappeared several times in proposed NASA spacecraft. When engineers at the Langley Research Center revealed their HL-20 design for a mini-shuttle, or crew return vehicle, in 1990, the shape was remarkably similar to HL-10 and X-24A designs. The same was true for the X-38 emergency crew return vehicle, which NASA began developing in the late 1990s for the International Space Station. And even Lockheed's proposed X-33 single-stage-to-orbit, reusable launch vehicle – a late 1990s research effort that was envisioned to be a replacement for the space shuttle – featured a lifting body design.

Dryden's research proved that this unconventional type of spacecraft not only could be flown and controlled, but also offered an efficient configuration for a reusable launch vehicle. As with many cutting-edge research efforts, the concept is now proven and awaits only the right mission in order for the technology to be applied in an operational vehicle.

Speed and the SST

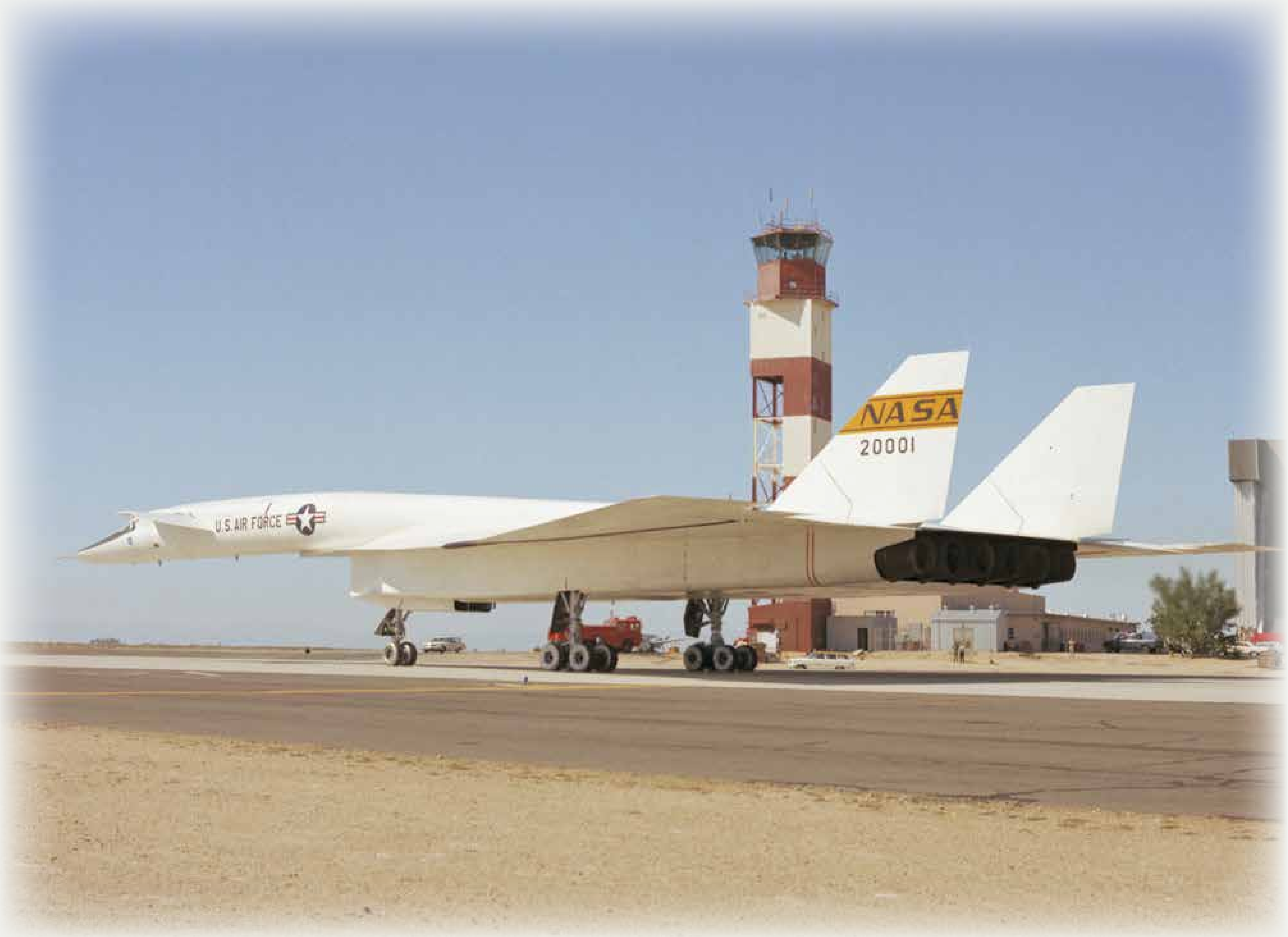
At the same time Dryden engineers were researching high-speed, horizontal-landing spacecraft, they also were pursuing high-speed research in support of a more pragmatic application: a supersonic airline transport. Advances in jet engines and jet-powered aircraft had given rise to ideas about a supersonic airliner in engineering design shops around the world, including those in Europe and the Soviet Union. To ensure that the U.S. remained competitive, President John F. Kennedy signed an initiative in 1961 – the same year he issued his famous lunar challenge – for the U.S. to produce a national Supersonic Transport (SST) capable of flying three times the speed of sound.

Speed and the SST

Dryden's first effort in support of that program was a series of flights with a Navy A-5A Vigilante to explore the approach and let-down problems that might occur with an SST in a crowded air traffic environment. Over the course of several months, Dryden research pilots flew the aircraft on a series of supersonic approach profiles both at Edwards and into Los Angeles International Airport.

The next phase of Dryden's SST-related research involved work with North American Aviation's XB-70. Work on this supersonic, intercontinental bomber had begun at North American even before President Kennedy's initiative. The XB-70 was a mammoth six-engine aircraft made primarily of honeycombed stainless steel, weighing more than 500,000 pounds and capable of speeds in excess of Mach 3. It featured an advanced design that incorporated two vertical fins, a canard, and a highly swept delta wing with drooping tips. Before the bomber went into production, however, the program was canceled. Nevertheless, the Air Force funded the two XB-70 prototypes to be used as research aircraft.

Research pilots Fitz Fulton, left, and Don Mallick walking away from the XB-70A aircraft on December 23, 1968. (NASA photo EC68 2140)



An XB-70 Valkyrie research airplane taxis past the Edwards Air Force Base tower on its first NASA flight, April 25, 1967. (NASA photo EC67 1684)

The XB-70A Valkyrie, as each prototype was officially designated, appealed to researchers because its configuration closely matched many elements a supersonic transport could be expected to include. The XB-70 flight research was to be another joint effort between Dryden and the Air Force Flight Test Center, and research instrumentation was incorporated into the prototype from the start. The plan called for the Air Force to manage the initial test, evaluation, and early research flights with the airplane, with NASA eventually taking over management of one of the two aircraft.

The XB-70A

In February 1963, the NASA Flight Research Center acquired this Lockheed JetStar four-engine business jet and sent it to the Cornell Aeronautical Laboratory in Buffalo, New York, to have it converted into a general purpose airborne simulator (GPAS). Shown on the Rogers Dry Lake in November 1964, this aircraft was later used in work in conjunction with an XB-70A to simulate a supersonic transport, with the XB-70 acquiring data to correlate and validate that from the GPAS. (NASA photo EC64 0263)

The XB-70 earmarked for NASA's use was scheduled to be turned over to Dryden in mid-June 1966. But on June 8, 1966 the Valkyrie was involved in a disastrous mid-air collision with a NASA F-104N piloted by Dryden's veteran chief pilot Joe Walker. The XB-70, an F-4B, a YF-5A, and a T-38A had assembled for an in-flight photo of the military aircraft powered by General Electric aircraft engines. Following a separate mission Walker joined up with the other planes for the photograph and positioned his F-104 just off the XB-70's right wingtip. Suddenly, Walker's F-104 was drawn in toward the bomber by the invisible wake vortex of its enormous wing; his aircraft collided with and sheared off both of the Valkyrie's vertical stabilizers, continued to roll over, and fell away in flames. Walker was killed instantly. The XB-70 went out of control and crashed. Of the three pilots involved – Walker, in the F-104, and North American test pilot Al White and Air Force Maj. Carl Cross in the XB-70 – only White survived, and he was seriously injured. In less than two minutes, the Air Force and NASA had lost two aircraft, and even worse, two talented pilots.

The accident was a severe setback for the joint research program. The remaining XB-70 was neither as capable nor as well instrumented but by default became the primary research aircraft. The Air Force and NASA flew it for several months in late 1966 and early 1967 to test the ground impact of its sonic boom at different altitudes and speeds – research that helped determine that the American public would not tolerate overland supersonic flight.

The next flight research phase with the XB-70 concentrated on verifying drag predictions for the aircraft. In April 1967, Dryden began a series of flights with the airplane to correlate NASA wind tunnel and simulator predictions computed at Ames and Langley. In the most comprehensive drag-correlation effort ever attempted for supersonic cruise configuration, researchers discovered that the general drag predictions for cruise conditions were fairly close, but that the actual drag of the aircraft as it went through the transonic peak drag phase was 27 percent higher than predicted. Those numbers were sobering as well as unexpected, and pointed to a clear area of potential difficulty for any future promoters or designers of supersonic transport aircraft.

The YF-12A

Flight research with the XB-70 also examined the structural dynamics of the aircraft at high speeds, investigating methods aircraft manufacturers might use to reduce vibration in the structure of future supersonic aircraft. By the end of 1968, however, research results no longer justified the program's cost. Dryden was also beginning research with a Mach 3-capable Lockheed YF-12A, which was capable of yielding much of the same high-speed data. The XB-70A was retired.

The YF-12A was the prototype of a fighter/interceptor version of the SR-71 Blackbird spy plane that, while introduced in 1964, was the world's fastest jet-powered aircraft even at its retirement in 1998. Because its routine operations at altitudes above 80,000 feet and speeds of Mach 3 subjected it to extremely high temperatures, the aircraft was constructed of titanium and painted a characteristic flat-black color. In the mid-1960s – and, indeed, for many years after – the YF-12 and SR-71 programs were highly classified. But fortunately for NASA, Blackbird program personnel decided they needed help from NASA on a flight test program they were conducting at Edwards. Dryden managers asked if they could have access to an SR-71 for their own research while aiding the Air Force effort. Though Air Force officials declined that request, they offered Dryden the use of two YF-12s in storage at Edwards.

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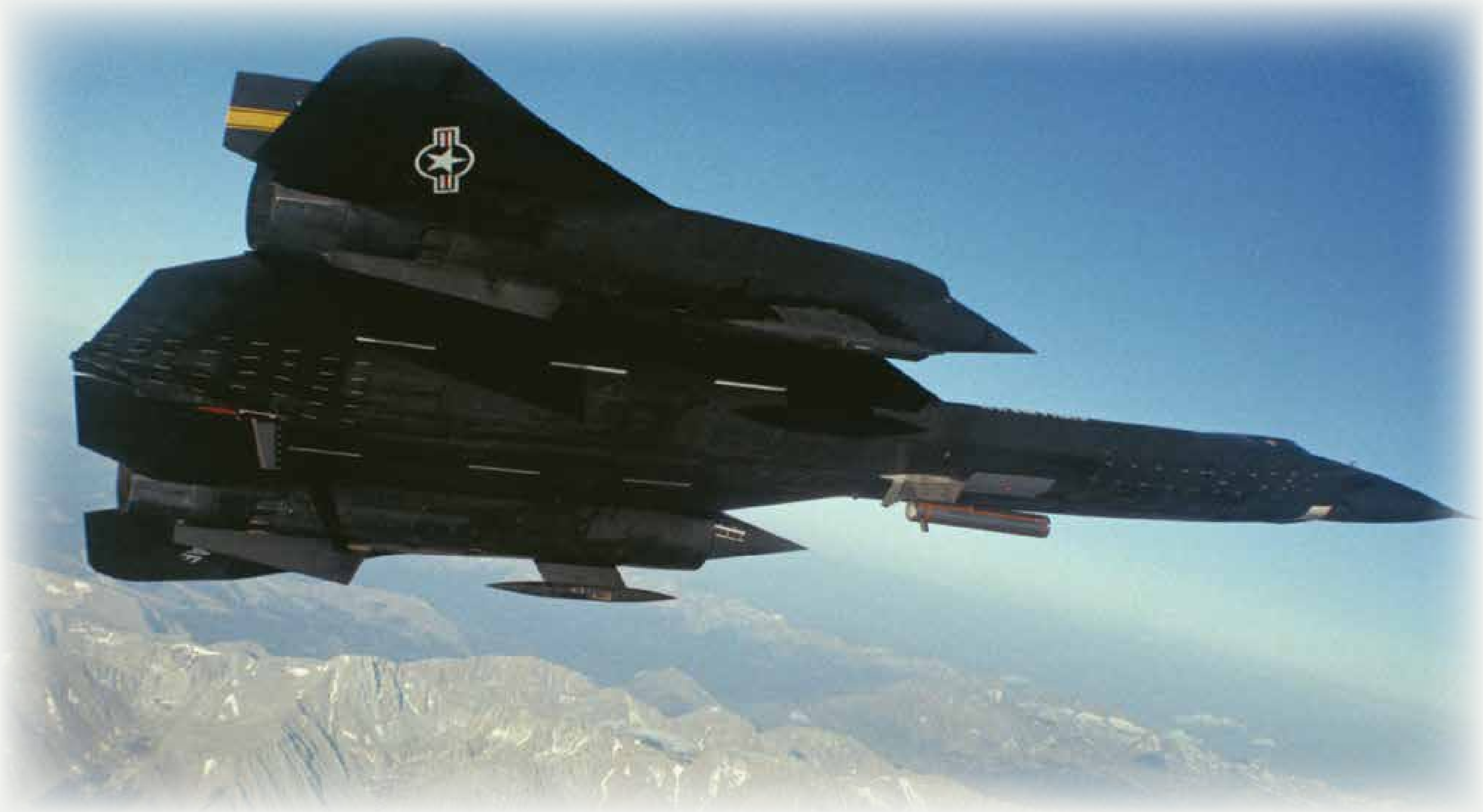
A Lockheed "YF-12C" (actually an SR-71A) flies over the Sierra Nevada Mountains on June 8, 1973. The Air Force made this aircraft available for propulsion testing but disguised its use by requiring that it be called a YF-12C. It completed 89 joint NASA-Air Force flights between July 16, 1971, and December 22, 1978. (NASA photo EC73 3667)



YF-12A Number #935 on July 11, 1975, conducted the "Coldwall Experiment" in which a hollow cylinder beneath the aircraft gathered flight data about heat transfer and skin friction to compare with theoretical findings and data from wind tunnels. (NASA photo EC75 4731)

So two days before Neil Armstrong walked on the moon, Dryden found itself with two Blackbirds and yet another joint research effort with the Air Force. The partnership also included several other NASA centers interested in the data the YF-12 flights might generate. Langley wanted data on aerodynamics and structures, Lewis (now Glenn Research Center) on propulsion, and Ames on the aircraft's complex engine inlet aerodynamics, as well as data to correlate its high-speed wind tunnel predictions.

The YF-12 flights at Dryden provided information about numerous areas, including aerodynamic loads and structural effects of sustained Mach 3 flight, thermal loads, the dynamics of the engine inlet system, and stability and control issues. The YF-12 had a very narrow flight envelope at high speeds, and if the stability augmentation system failed, the aircraft could become very difficult to fly.

Complex Engine Inlets

A serious issue in performing structural research on the YF-12 was how to separate the structural strains caused by thermal loading from the strains caused by aerodynamic forces. A major test effort was performed in the Dryden Flight Loads Laboratory that used high-temperature quartz lamps to heat half of the YF-12 vehicle, creating the temperature profile experienced in flight. Under these thermal conditions—without the aerodynamic loading—researchers were able to measure the thermal loads and separate the two sources of strain for follow-on structural research.

The Blackbird also had complex engine inlets.

At the center of each inlet was a cone, dubbed a spike, that moved fore and aft depending on the aircraft's speed, altitude, attitude, and other factors. The spikes' positions were critical to engine operation and if either spike were incorrectly positioned it led to an unpleasant phenomenon known as an *"inlet unstart."* This occurred when the shock wave formed by the aircraft's high-speed flight jumped from its normal position just inside the inlet to outside the inlet opening. One pilot described an unstart as *"like a train wreck"* because it jolted the aircraft so badly, for they invariably happened at supersonic speeds and caused the aircraft to yaw dramatically. The work at Dryden resulted in a digital inlet controller on the SR-71.[1]

As the flights progressed, the YF-12 also was used as a testbed for additional *"piggy-back"* research experiments, just as the X-15 had been. One notable project involved super-cooling an insulated test fixture on the aircraft before takeoff, then explosively removing the insulation once the aircraft reached Mach 3. This *"coldwall"* research, which managed to achieve laboratory standards 14 miles above Earth's surface, became a benchmark heat transfer and fluid dynamics experiment.

The YF-12 research program experienced fewer problems and greater successes than the XB-70A effort, with almost 300 flights and 450 flight hours completed in nine years. But both aircraft offered researchers the chance to explore a realm no other aircraft – not even the X-15 – had been able to breach: sustained flight at speeds of Mach 3. The data obtained through those flights greatly enhanced researchers' understanding of the problems involved in extremely high-speed flight and expanded the nation's high-speed aeronautical knowledge base. These contributions will significantly benefit the performance and safety of any future aircraft designed to fly in that realm.

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An F-104B flies on a test mission, June 23, 1966. (NASA photo EC66 1298)

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This F-104A, flying on December 9, 1965, was one of eleven F-104s flown over the years for both research and safety chase purposes. (NASA photo EC65 1048)

The F-8

In the early 1970s, however, two events dramatically shifted the nation's priorities – and with them, Dryden's research focus on aeronautics. First, Congress cancelled the SST program funding on March 24, 1971. The project had run into strong opposition from communities and groups concerned about the environmental impact of such an aircraft, making the project politically untenable. As a result, high-speed experiments became a much lower national priority.

Second, the gas crisis of the early 1970s suddenly made speed a far lower priority in air travel than fuel efficiency. That shift in focus, from speed to efficiency, has endured to the present. The speed of most current airliners has not increased materially over the jetliners that were on the market in the 1960s. Most improvements made since then have been in the areas of efficiency, avionics, flight controls, systems, and safety. Fortunately, Dryden was able to shift its research focus along with the nation's and industry's changing needs, allowing the center and its researchers to continue making relevant and significant contributions to advances in the U.S. air transport industry.

Efficiency

One of the efficiency-related concepts that Dryden helped to explore in the early 1970s was the Supercritical Wing (SCW). The SCW was an idea developed by Dr. Richard T. Whitcomb, a research engineer at Langley Research Center. Whitcomb theorized that a wing could be shaped to modify shock-wave formation and associated boundary-layer separation (where air flow *"separates"* from the wing), and therefore delay the typically sharp increase in drag that occurred as an aircraft approached the speed of sound. If the rise in drag could be delayed, it would make a transonic aircraft more fuel-efficient. That efficiency, in turn, would allow the aircraft to either increase speed or range or decrease the amount of fuel needed for flight.

Whitcomb had worked on the concept since the early 1960s and had tested numerous shapes in Langley's wind tunnels. But he wanted to test his idea in actual flight conditions. The aircraft finally selected for the experiments was a Vought F-8A Crusader, an older Navy jet fighter that performed easily in the transonic range. The Crusader also had a distinctive variable-incidence wing, raised by a hydraulic actuator to allow the aircraft to land at a slower speed with better cockpit visibility. This feature meant that the Crusader's wing could be replaced with a test airfoil much more easily than the wings of most aircraft.

Since Whitcomb's smooth, supercritical airfoil could not integrate the F-8's adjustable-wing feature or flaps. The F-8 SCW needed an extraordinarily long landing and takeoff area. One of the main reasons the F-8 SCW research was conducted at Dryden instead of Langley, where Whitcomb worked, was Dryden's access to exceptional high-speed takeoff and landing facilities. The modified F-8 could take off from Edwards' 15,000-foot paved runway toward Rogers Dry Lake and could land on the lakebed.

Dryden actually acquired four F-8 Crusader aircraft, and the one modified with a supercritical wing. It began its flight research in March 1971. The program showed promise, and follow-on flights incorporated fairings on the fuselage to give it a more efficient shape. The F-8 work initially focused on the use of a supercritical airfoil to increase the cruise speed of an airliner, and the Dryden flight research indicated that a transport aircraft with a similar airfoil design could, indeed, see a 20 percent increase in speed. But even as the research was being conducted, the price of oil tripled. Airlines suddenly wanted fuel efficiency, not speed. So Whitcomb modified the wing design for maximum aerodynamic efficiency. The modified wing showed the potential for substantial fuel savings, and the design was subsequently incorporated into a wide range of transport airplanes.

The Vought F-8 Crusader was significantly modified to support supercritical-wing flight research in December 1972. (NASA photo EC72 3417)

At the same time the F-8 SCW research was investigating the civil applications of a supercritical wing, the military was beginning a research effort called the Transonic Aircraft Technology (TACT) program. The TACT research involved applying a supercritical wing to a General Dynamics F-111 to see how the concept might benefit military aircraft. The F-111 was chosen because, like the F-8, it had an easily replaceable wing. Furthermore, the Air Force was looking for retrofit technology that could improve the performance of its active-duty F-111s. The TACT program was a joint effort that, in addition to Dryden, involved the Air Force Flight Dynamics Laboratory and Ames Research Center, which undertook the development of the advanced wing configuration.

Flight research with the F-111 TACT began in February 1972. Three years of flight research revealed that a supercritical wing could improve the performance of a military aircraft, generating up to 30 percent more lift than a conventional F-111 wing. The research also showed that attaching external munitions to the wing did not cancel these gains, and that a supercritical wing did not degrade aircraft performance at supersonic speeds. Ultimately, the Air Force decided not to retrofit the F-111s.

Aviation Safety

Dryden's initial focus on high-speed flight meant that it was less involved in civil aviation in its first two decades – especially the smaller, non-commercial aircraft that comprise what's known as General Aviation (GA). But by the late 1960s, Dryden's research focus had expanded and diversified considerably. At the same time, the aviation community was becoming increasingly concerned about the growing number of accidents among GA aircraft. In an effort to determine whether common design weaknesses or problems could be identified in GA airplanes, Dryden was asked to investigate the handling characteristics of several designs throughout their respective flight envelopes.

Dryden pilots test-flew a total of seven GA aircraft, and the results showed no single weakness or problem, confirming that the designs were generally adequate. However, while the research wasn't intended to point out design flaws in particular models, the flights also resulted in the side benefit of uncovering several problems with the test-aircraft designs. One aircraft, for example, developed a serious flutter in its horizontal stabilizer while still within normal operating limitations, and the poor stall-spin characteristics of another twin-engine aircraft led its manufacturer to modify the design with contra-rotating propellers.

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The Flight Research Center's Aero-Commander flies a general aviation study with tufts on the fuselage to show actual airflow while in flight on Aug. 27, 1968. (NASA photo EC68 2118)

Another safety concern that began to draw more attention in the late 1960s and early 1970s was the phenomenon of wake vortices. Wake, or wingtip vortices are powerful tornado-like disturbances in the air spinning off the wingtips of an airplane. The bigger and heavier the airplane, the more powerful these disturbances become, and a small plane traveling too closely behind a larger one can easily be flipped upside down by the vortices at the edges of the larger aircraft's wake. Wingtip vortices are a particularly dangerous hazard during approaches or departures from airports, since trailing aircraft have little altitude in which to recover from unexpected upsets. So as jumbo jets were introduced into the nation's air traffic system, the aviation community began looking for more detailed information on the behavior and strength of wake disturbances generated by large aircraft.

Investigating Wake Vortices

In late 1969, Dryden pilots began investigating wake vortices by flying an instrumented F-104 fighter behind a B-52 bomber. The project expanded to include an early model of the Lockheed C-5 Galaxy, whose vortices were so strong that on one flight they caused the F-104 to roll inverted and lose between three and four thousand feet of altitude before the pilot could reassert control, even though the fighter was flying 10 miles behind the larger airplane. In 1973, Dryden again expanded its wake vortex research to include a Boeing 727, and the following year researchers conducted another series of tests flying a Learjet business plane and a T-37 Air Force jet trainer behind a Boeing 747. After the 747's wake induced two unplanned snap rolls in the T-37 and caused it to develop a roll rate of 200 degrees per second despite the fact that the trainer trailed the jetliner by more than three miles, one research pilot speculated that a safe separation between the two aircraft in a landing configuration would have to be three times that distance.

As more jumbo jets entered service, Dryden expanded the research to examine the wake vortices of Lockheed's L-1011 and McDonnell Douglas' DC-10. Follow-on flights looked at how use of landing gear, wing flaps, speed brakes, or spoilers affected the formation and behavior of wing vortices, although researchers were unable to find an aerodynamic solution that was both practical and effective. The result of Dryden's research led to an FAA-mandated minimum separation distance of aircraft in the landing pattern at airports around the country. The degree of separation is mainly a function of aircraft size and speed, factors established by Dryden's research.

In 1973, Dryden researchers conducted one additional flight safety research effort for McDonnell Douglas and the Air Force. It was a relatively small project on paper, but it was a harbinger of a kind of research that would become prevalent at the center in years to come. McDonnell Douglas and the Air Force were in the midst of the F-15 Eagle fighter development program, they wanted to test the design's spin characteristics on a scale model before committing to a piloted test program. Dryden had experience with remotely piloted vehicles (RPVs) and a modified B-52 launch aircraft capable of air dropping such a model. So McDonnell Douglas and the Air Force contracted with Dryden to conduct a series of flight and spin tests on three remotely piloted, 3/8-scale F-15 models. The tests were successful, and the results gave McDonnell Douglas and the Air Force the confidence they needed to go ahead with a spin test program on a full-scale, piloted F-15.

At the time, flight research involving remotely piloted vehicles and/or scale models of larger designs was not that common at Dryden – or anywhere else, for that matter. A quarter-century later, however, this kind of scale-model approach to testing of a new concept would be the rule rather than the exception, and remotely piloted vehicles would start to dominate the center's flight schedules and hangar space.

A Boeing 747, followed by a Cessna T-37 and a Gates Learjet, conducts wake vortex studies on September 20, 1974. (NASA photo EC74 4246)

Digital Fly-By-Wire

The most revolutionary change to sweep across the desert at Edwards in Dryden's third decade, however, was the advent of the computer age. The basic external configuration of most aircraft has stayed fairly constant since the 1930s. The inner workings of new aircraft, however, represent a radically different machine. New models may resemble their predecessors on the outside, but the propulsion systems, flight controls, avionics, and displays of contemporary aircraft are aided and controlled by computers, giving these new designs vastly improved performance, maneuverability, safety, and efficiency. Researchers at Dryden did not invent computerized flight control systems, but they did conduct the first flight of a strictly digital fly-by-wire aircraft, and have continued to play a critical role in development and validation of computerized aircraft systems and technologies.

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SUPERCRITICAL WING

The F-8 Digital Fly- By-Wire aircraft, left, and the F-8 Supercritical Wing aircraft fly in formation on Jan. 10, 1973. This picture also underscores the dramatically different shape of a supercritical wing. (NASA photo EC73 3500)

The Digital Fly-By-Wire (DFBW) program at Dryden began in the late 1960s. A fly-by-wire aircraft uses electronic signals instead of mechanical links to connect the pilot's control stick to the airplane's flight control surfaces. When the pilot moves the stick, an electronic command is sent to the appropriate control surface actuators to command a corresponding movement. The signals are first processed through a flight control computer, which can contain sophisticated systems that would be impossible with a simple mechanical system.

Dryden's researchers had worked on analog fly-by-wire systems on the Lunar Landing Research Vehicle (LLRV) program, and both the aerospace industry and the research communities were interested in applying computerized flight control systems to aircraft. In 1969, a group of Dryden engineers developed a plan to investigate use of an analog flight control computer in a new research airplane. Using an unconventional aircraft configuration would demonstrate not only the feasibility of a computerized control system, but also the advanced and even unstable configurations the technology would allow. The proposed research vehicle was a modified Vought F-8 Crusader with a canard and ventral fins in place of a conventional tail structure.

The researchers proposed the idea in late 1969 to NASA's deputy associate administrator for aeronautics within the Office of Advanced Research and Technology, who happened to be Neil Armstrong. Armstrong asked why the group was proposing an analog computer system instead of a more advanced digital system. The researchers explained that no flight-capable digital computer existed. Armstrong reportedly observed that we had just gone to the moon using a digital control system, and asked if the team had looked at the Apollo system. The Dryden engineers had not, but shortly after that exchange with Armstrong, they contacted the Draper Laboratory, the Massachusetts Institute of Technology's advanced lab that had developed the Apollo computer, asking for the computer's specifications and other details.

NASA Headquarters approved the digital fly-by-wire research, but with a conventional F-8 aircraft. The Crusader aircraft proposed by Dryden was simply too radical, and in fact was probably too advanced to be successfully implemented in 1970. Interestingly enough, however, the thrust-vectoring X-31 built by Rockwell in the late 1980s shared numerous design elements with the company's earlier DFBW airplane concept.

Removal of Mechanical Links

The basic concept of fly-by-wire aircraft control systems was not new in 1970. Aircraft had been flying for years with autopilot systems that were, in essence, simple fly-by-wire designs. Bombardiers in World War II relied on simple fly-by-wire systems to fly aircraft precisely over a target area. But those designs were part-time and limited control systems rather than actual stand-alone flight control systems. The primary system linking the pilot's inputs to the aircraft's flight controls still was mechanical. Some aircraft had control systems that were boosted by hydraulic or electric power, but these, too, were mechanically linked to control surfaces.

What made the F-8 DFBW such a significant leap forward was that Dryden removed all the aircraft's mechanical control linkages and replaced them with electronic systems. The decision to rely entirely on electronic systems was made for two reasons. First, it would force research engineers to focus on the technology and issues that were going to be truly critical in a production-model fly-by-wire aircraft. Second, it would give industry confidence in applying the technology. If an experimental system could not rely entirely on digital electronic technology, it would suggest that digital fly-by-wire was still beyond reach. Consequently, Dryden researchers decided the F-8 DFBW would have to be a strictly fly-by-wire aircraft.

The DFBW program consisted of two phases. The first goal was simply to prove that a DFBW aircraft could be flown safely and effectively. For this initial phase, the Apollo 15 digital flight control computer served as the primary system, with a Sperry analog flight computer based on the design used in the center's lifting body vehicles as a backup. In addition to being a proven system, the Apollo computer had the advantage of an incredibly robust design.

Knowing that a computer failure in a spacecraft would be disastrous, Draper Laboratory engineers designed the system to have a demonstrated mean time between failures of more than 70,000 hours. Its robust design meant the Apollo computer would be far too heavy and expensive for use in a production aircraft, but it gave researchers far more confidence in flying a fully fly-by-wire aircraft for the first time.

The tie-in to the Apollo system also had another, even more significant, advantage for Dryden engineers working on the project. In retrospect, the project staff acknowledged that they had underestimated the effort involved in designing a full fly-by-wire system from scratch. But by using Apollo hardware, they were able to tap into a multi-billion-dollar, seven-year research effort that had already faced and tackled many of the problems inherent in computerized flight control systems.

One of the first things Dryden engineers realized after deciding to eliminate all mechanical links in the F-8 DFBW, for example, was that software verification and validation would be the program's single most critical issue.[2] How, exactly, to create software that would have no critical errors in it? Nobody had ever designed a flight-critical system through which a small software error could cost somebody's life. Nobody, that is, except the M.I.T. Draper Laboratory, which had created an extensive software development process to address that very issue with the Apollo system. Using Dryden's specifications and the processes developed for the Apollo program, engineers at the Draper Lab developed the software for the F-8 DFBW program. Dryden engineers, in turn, adapted those methods to develop all subsequent flight control system software used at the center.

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FLIGHT RESEARCH CENTER

The F-8 Digital Fly-By-Wire aircraft flies on January 10, 1973. (NASA photo EC73 3478)

The Triplex DFBW

The F-8 DFBW flew for the first time on May 25, 1972, and the first flight and the phase one flights that followed were very successful. After the F-8 successfully demonstrated the feasibility of a fully digital fly-by-wire system, the second phase of the program began. This segment involved replacing the Apollo hardware with a triply redundant digital computer system that would be closer to what might be used in a production aircraft. By the time phase two modifications began, between 1973 and 1974, General Dynamics had designed the analog fly-by-wire F-16 fighter, and digital flight computers were being developed for other aircraft. For the F-8 system, Dryden engineers selected three IBM AP 101 computers.

Switching from the single Apollo computer to a triplex fault-tolerant DFBW system using three IBM computers was more difficult than researchers anticipated, however. In addition to other issues, the AP 101s were prototypes of the company's newest digital computers designed for use in an aircraft. Not surprisingly, they were not without flaws. When one of the three computers failed on the F-8's second flight and several failures occurred during ground tests, the aircraft was temporarily grounded.

But after a manufacturing problem with the computers was found and corrected, the F-8 DFBW resumed its successful flight research career. And although it was an unintended benefit, detecting and fixing the IBM computer problems benefited the space shuttle program as well. A year after the IBM AP 101 computers were selected for the F-8, shuttle program managers chose the same equipment for the shuttle flight control system, a decision heavily influenced by Dryden engineers' success with their DFBW program. The F-8 DFBW research served as a path-finding project that provided actual operational data to the space shuttle program. It also gave IBM a chance to work out problems in the hardware before it was installed in the orbiters.

The triplex DFBW system was a learning experience in many ways. Engineers had to figure out how to synchronize the computer, sensors, and hydraulic actuators to make them all work together; they had to invent new ways to test and diagnose problems that occurred; and they had to make sure that a problem in one part of the system did not propagate to the rest of the system. But most of all, they had to develop the process and techniques to build a complex hardware and software system and prove that it would be safe for human flight. The insights gained during this project laid the foundation for all subsequent multi-channel DFBW systems.

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The display and keyboard (DSKY) unit from the Apollo computer used in the primary flight control system for Phase 1 of the F-8 Digital Fly-By-Wire flight research included warning lights that would appear in the upper left section, displays in the upper right, and the keyboard constituted the lower section. (NASA photo EC96 43408-1)

More mundane things were learned, too. DFBW electronic controls were often initially more sensitive than their mechanically controlled counterparts. This resulted in over control, and could lead to pilots inducing a divergent oscillation, or PIO. Software modifications to the way the pilot stick commands were processed solved these problems. Verification and validation of the DFBW software and hardware became life-critical, but the F-8 DFBW project proved it could be done with new development techniques, new test techniques, and especially, extreme rigor and discipline, as had been achieved in the Apollo program for spacecraft.

The advent of computerized flight control systems has allowed advanced aircraft designs to do things they could never do before. Aircraft ranging from high-performance military vehicles to commercial airliners are safer and in many cases easier to fly because of the presence of computerized flight control systems. But it also means that software for computerized flight control systems, particularly the pilot response coupled with that of the computerized flight control systems, has become a critical element in systems design, as critical to an aircraft as the spar in its wing.

Private-sector Interest

As with other Dryden research aircraft, the F-8 DFBW also proved a valuable testbed and resource after the program's initial flight research goals were achieved. It was in service for 13 years, during which it was used to help develop many other pieces of technology. The proposed side-stick controller for the F-16 fighter was tested in the F-8 to determine whether it would be acceptable to pilots, and NASA engineers also used the aircraft to test various new control laws they had developed. In some cases, pieces of technology that were simply developed out of necessity for the F-8 were picked up by manufacturers or for use in other research programs. The Resident Back-Up Software (REBUS) was meant to keep the three computers operating even after a software failure that was common to all three computers. This novel system flew only six or seven times, but that demonstration was sufficient for the concept to be incorporated into several experimental and production aircraft.

Probably the most significant contribution of the F-8 DFBW program was simply proving the feasibility of a DFBW aircraft and giving the technology enough credibility to encourage private-sector interests to incorporate computerized flight control systems in new aircraft designs. That process also was greatly aided by the personal contact Dryden engineers had with industry personnel throughout the program. There was great interest in the DFBW technology, and industry engineers were on the phone regularly with their Dryden counterparts during the F-8 program learning not only about the technology itself, but also about the processes used at Dryden to develop the F-8 systems. And as Dryden engineers collaborated with many companies on subsequent flight research programs, the original Draper Lab/Apollo software development processes began to be incorporated by numerous industry manufacturers.

In 1978, six years after the F-8 DFBW made its maiden flight, the McDonnell Douglas F-18 Hornet became the first production digital fly-by-wire aircraft. Other aircraft followed. At its most basic level, fly-by-wire technology reduced the weight and maintenance costs of aircraft by replacing heavy mechanical systems with lightweight wires. But its real significance was its impact on aircraft design and performance. Fly-by-wire technology made the first inherently unstable fighter, the F-16, possible. Development of the highly maneuverable X-29 and X-31, as well as the F-117 Stealth Fighter and B-2 Stealth bomber, the F-22 Raptor, and the F-35 Lightning II Joint Strike Fighter would not have been possible without computerized flight control systems.

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The Lockheed "YF-12C" flies on June 8, 1973, where it tested performance and a low lift-over-drag approach. (NASA photo EC73 3678)

Digital Engine Control

As Dryden controls engineers were investigating the possibilities of using computers to aid flight control systems, propulsion engineers were looking at the same kind of technology to improve aircraft engine performance. Soon after the F-8 proved it was possible to fly an aircraft with an electronic flight control system, Dryden began an Integrated Propulsion Control system (IPCS) effort with a General Dynamics F-111E to examine the potential of electronic engine control.

Digital Engine Control

The IPCS research program was an Air Force Aeropropulsion Laboratory initiative that ran from 1973 to 1976 and involved Dryden and Lewis (now Glenn) Research Center, Pratt & Whitney, Boeing, and Honeywell. An F-111 was chosen as the research plane because it was one of the few Air Force aircraft with variable inlets and two turbofan engines. That allowed one engine to be modified, with the second as a backup in case something went wrong.

Interest in digital engine control was driven by the same motivations fueling digital flight control research. Computerized systems could not only control the operation of an aircraft or engine more precisely and therefore efficiently, but could also allow integration of multiple components. Integrated systems would allow pilots to simply command what they wanted the aircraft to do and leave it up to the *"smart"* controls to execute whatever combination of power and flight controls were necessary to make that happen. Such technology would give an aircraft vastly expanded capabilities.

The F-111 IPCS program replaced the hydromechanical controls for inlet position, fuel flow, and afterburner on one of the aircraft's engines with a computerized, electronic system. The goal was simply to see whether digital engine control could increase engine performance by operating it more efficiently while still functioning as reliably as a mechanical control system. As with many pioneering concepts, the F-111 IPCS system was rudimentary. And though it was not ideal, the research still proved the worth of the basic Digital Electronic Engine Control (DEEC) concept. Even at its worst, the technology still performed as well as a conventionally controlled engine.

The research was the first step in a technological revolution that would transform aircraft propulsion possibilities, and therefore aircraft design. The integrated and intelligent flight controls that vastly improve the safety and performance of transport and fighter aircraft, as well as the engine and control technology that make highly capable unmanned aerial vehicles (UAVs) like the Global Hawk possible all stem from that early research at Dryden in digital engine and flight control.

At the time, neither Dryden researchers nor their industry counterparts could have foreseen all the future applications for their efforts. But Dryden's rudimentary experiments with the DFBW and the IPCS were, in fact, laying critical groundwork for paradigm-shifting changes in aerospace control, design, performance, and safety.

Conclusion

Among challenges inherent in the research business is striking the right balance between near- and long-term research efforts. If all of a publicly funded research institution's projects are aimed at technology that won't mature for 20 years and has no clear need driving its application, that institution may soon find itself without much support or funding. On the other hand, if an organization like NASA focuses only on popular or near-term projects, it endangers the nation's long-term technology base and growth. And for a research institution like Dryden, there is the additional need to balance work between subsonic and supersonic flight, propulsion and controls, aeronautics and space. It is a challenge that is never definitively or permanently resolved because balance is a dynamic pursuit in a changing environment, requiring constant adjustment and response.

Dryden may have begun life as a single-point design, as aeronautical engineers call an aircraft with a singular performance goal, but it was continuing to evolve into a more diversified research center. In the center's third decade, Dryden researchers found themselves looking at everything from advanced spacecraft designs to small, General Aviation aircraft modifications, pursuing both speed and fuel efficiency, and investigating both advanced configurations and advanced internal control systems. And while it may not necessarily have been a conscious strategy, the center leadership was discovering that by creating a good long-term mix of personnel, flight research facilities and resources, and research aircraft, Dryden could provide valuable, near-term assistance with unexpected problems or research needs that NASA, industry, or other government agencies might encounter in the midst of other programs or missions.

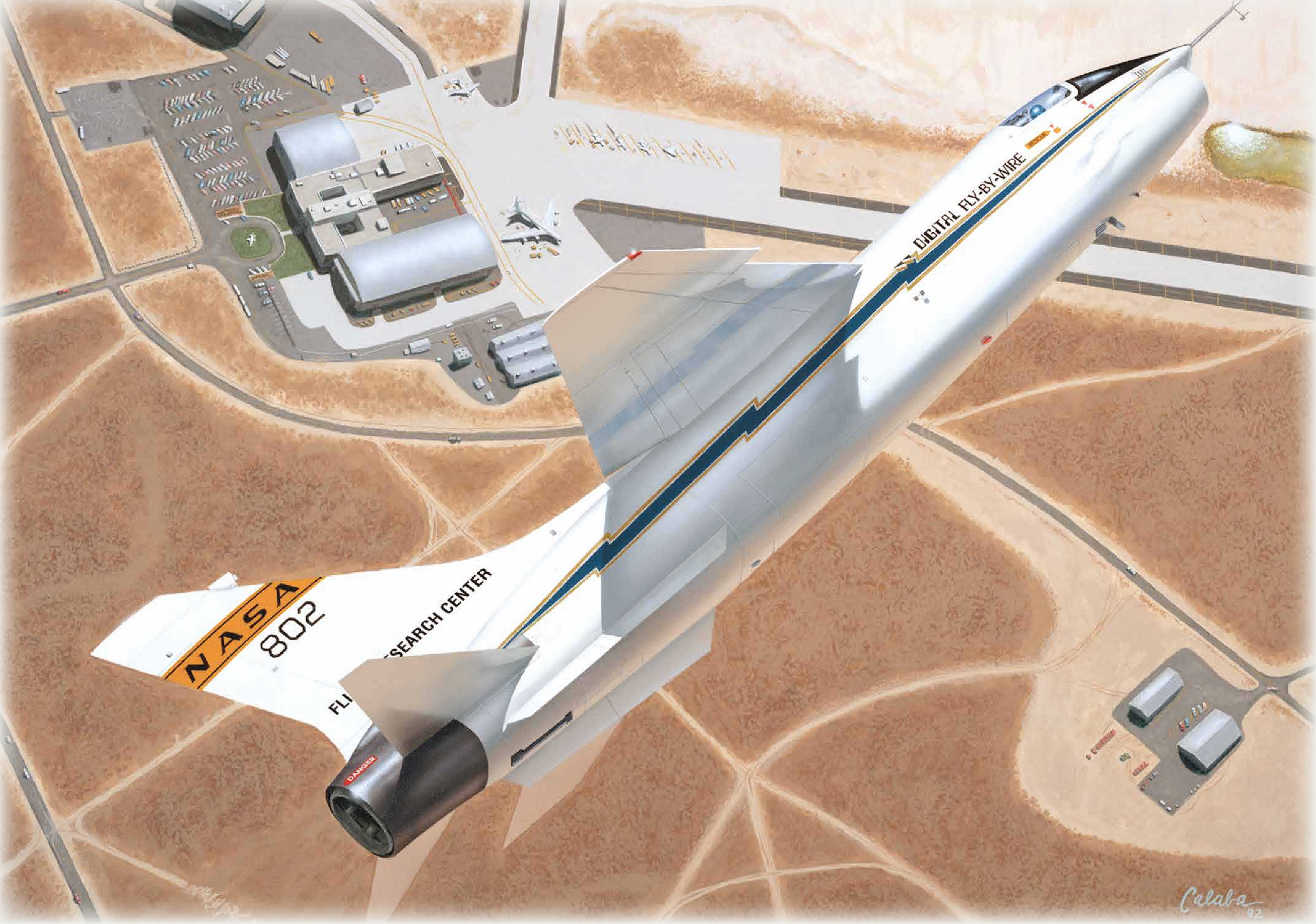
Conclusion

Slowly, Dryden was evolving from a specialized research facility into a national research resource, available to help investigate and resolve a growing range of questions and problems. Even research aircraft that had begun as dedicated vehicles for a particular program, like the B-52 mothership, the YF-12A, and the F-8 DFBW, were evolving into valuable testbeds and research platforms that were, in a sense, national resources in their own right.

Many of the seeds planted by the end of Dryden's third decade – an increasingly varied range of research, work with scale model and remotely piloted aircraft, use of research aircraft as testbeds and platforms for additional experiments or programs, growing capabilities as a quick-response research facility for unexpected, near-term problems or questions, and pioneering work in computerized flight and engine controls – would grow into defining themes at the center over ensuing decades. Though few of the researchers or managers who worked on those early programs could have foreseen all the changes their early efforts would lead to, few would have been surprised as the changes played out. Those who work at the center were, and still are, people of vision. They work at the edge of what is possible, looking ahead to what still might be. It's why they've been able to envision such a variety of creative solutions and concepts for flight in the atmosphere and space. And it's why such a small research center, located in the middle of a barren desert, appears so full of promise, always so vibrantly alive.

[1] Fitzhugh Fulton, interview with author, Edwards, CA, July 19, 1995.

[2] Verification and validation are both important tasks in flight research that are used to confirm new technologies, components, or systems before flight. A basic differentiation between the two tasks could be described this way: Verification is making sure the thing is done right. Validation is making sure it's the right thing that gets done.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Chapter 5

Efficiency, Control, Safety, and National Goals

F-8 Digital-Fly-By-Wire

by Dennis Calaba

Space and Aeronautics

In a sense, the beginning of the Dryden Flight Research Center's fourth decade marked the end of its formative years. By 1976, when the center was renamed in honor of former NACA Director Hugh L. Dryden, the facility's work had expanded to cover a broad spectrum of research – in space and aeronautics, speed and efficiency, configurations and systems, safety and performance, as well as piloted and unpiloted aircraft. Those research categories would endure as themes for the center's work throughout the decades that followed.

On the other hand, the constant of change still flowed like a current through the center's projects and facilities. National priorities continued to shift, and advances in technology continued to alter both the potential and the challenges inherent in new aircraft and spacecraft designs. Changes in NASA's budget and the national economy also continued to affect both Dryden's work and its organizational structure. So while Dryden's primary areas of research may have stabilized, center employees nevertheless had to continue adapting to an environment marked by new projects, new technologies, new partners, new priorities, and ongoing fluctuations in organizational structure and funding.

The Blue Room, one of two mission control rooms at Dryden, from which research and test flights are controlled (NASA photo EC04 0282-10)

The second half of the 1970s marked the beginning of a new era in space flight with the development of the space shuttle – a project to which Dryden contributed on several levels. The center's work on improving aircraft efficiency, safety, and performance continued, ranging from explorations into higher-performance wing shapes and devices to testing safer fuel additives for commercial airline operations. Dryden's work on computerized flight and engine controls kept pace with advancements in computer technology of the era, fostering work in the area of integrated computerized flight and engine controls. And as the lessons of the Vietnam conflict – including those gleaned through the poor performance of U.S. fighters in dogfights – began to register with military decision-makers, Dryden found itself exploring how computers and other advanced aircraft technologies could be configured to improve the maneuverability of future fighter aircraft. At the same time, the center found itself scrambling to adjust to changes in the federal budget climate that would involve, among other things, the temporary loss of Dryden's status as an independent NASA center.

Lee R. Scherer was Dryden center director from 1971 to 1975. (NASA photo ECN 2849)

Former astronaut David R. Scott was Dryden center director from 1975 to 1977. (NASA photo ECN 4502)

Former astronaut David R. Scott was Dryden center director from 1975 to 1977. (NASA photo ECN 9633)

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X-1E

Dryden's X-1E on a pedestal in front of the headquarters building in a rare instance of heavy snow that had fallen in the Mojave Desert. (NASA photo EC79 10170)

The Space Shuttle

Although the lifting body shapes explored and tested at Dryden in the 1960s and 1970s were not ultimately chosen as the configuration for the agency's new space shuttle, the center played an important support role in the shuttle program, starting with the first test flights of the shuttle orbiter in 1977. While Rockwell International was still in the process of building the first orbiter, the Air Force and NASA entered into an agreement establishing shuttle support facilities at Edwards Air Force Base. The clear skies, open landscape, and lakebed landing site at Edwards provided more leeway and options for returning shuttle pilots than could any other location. NASA planned to transport the shuttle between Edwards and the Kennedy Space Center launch site in Florida on the back of a Boeing 747, and the agency bought and modified one of the jumbo jets for that purpose.

The rollout of the prototype Space Shuttle Enterprise at the North-American-Rockwell (later, Rockwell international) plant in Palmdale, September 17, 1976. NASA Dryden flew the Enterprise in the approach and landing tests for the space shuttle during 1977. (NASA photo EC76-5872)

Computer and simulator calculations predicted that the mated shuttle/747 pair could fly together safely, but NASA wanted to verify that prediction in a controlled flight test environment before the shuttle went into operation. Researchers also wanted to glide-test the orbiter to ensure that it could execute a safe landing before attempting an actual mission. To accomplish both these goals, engineers at NASA's Johnson Space Center (formerly the Manned Spacecraft Center) designed a three-phase test program. The first, *"unmanned-captive"* phase would test the mated shuttle/747 with no crew in the orbiter so that in the event of a failure, the shuttle could be jettisoned. The second, *"captive-active"* phase would test the pair with a two-person crew aboard the orbiter. The third phase would be *"free-flight"* tests in which the orbiter and its two-person crew would be carried aloft on the 747 then launched off its back to glide down for a landing.

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The shuttle prototype Enterprise flying atop the Boeing 747 Shuttle Carrier Aircraft in the first captive flight of the Approach and Landing Tests, February 18, 1977. (NASA photo EC77 6823)

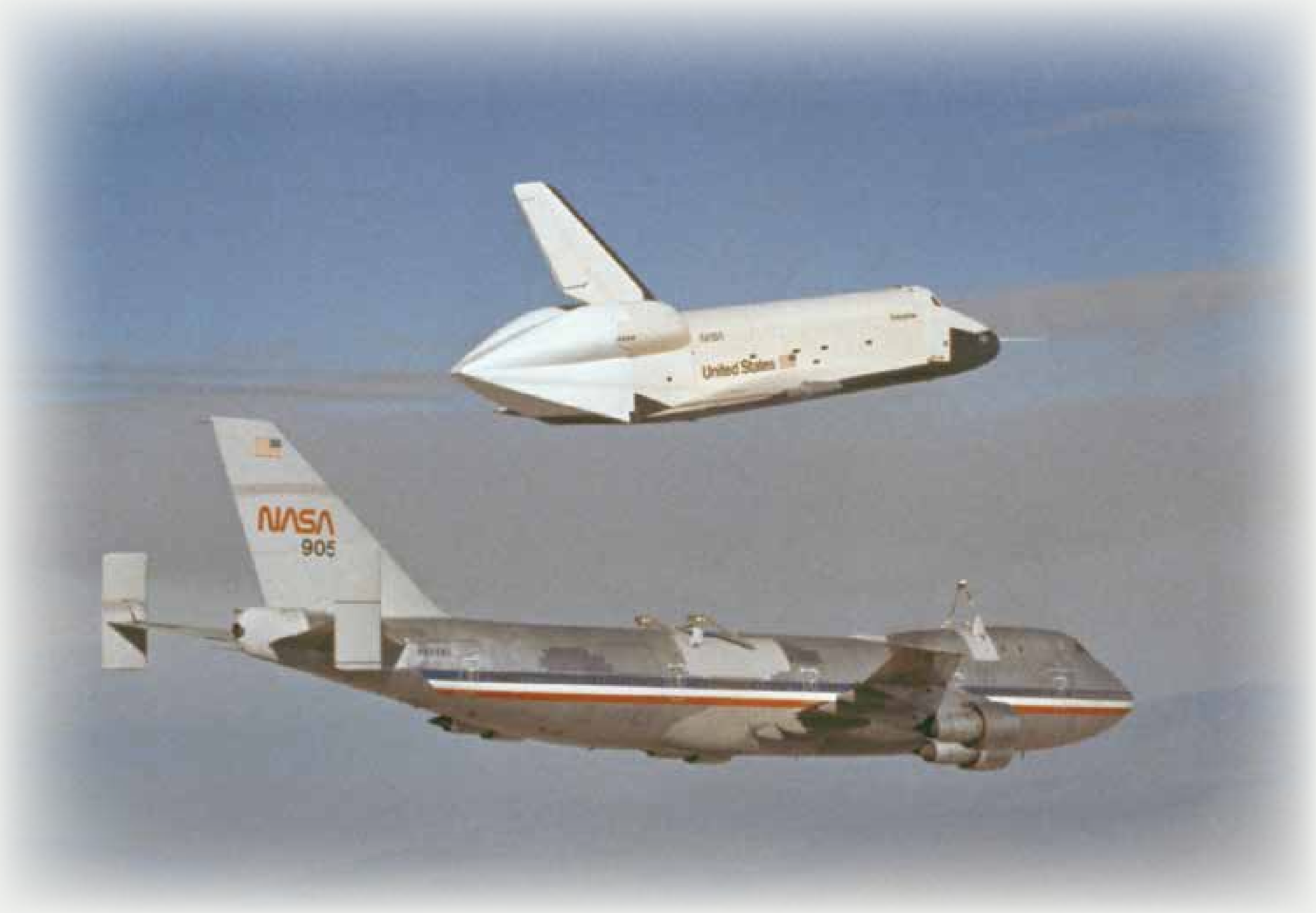
The Space Shuttle Air-Launch

As a safety precaution during the tests, a special escape system was installed in the 747. Ejection seats were impractical, particularly with the shuttle on top of the aircraft, so a laundry chute-like slide leading to an exit out the bottom of the plane was installed behind the cockpit. The pilots wore parachutes, and an explosive charge would blow a panel off the bottom of the chute/slide prior to an emergency exit. To ensure that pilots would reach the exit even if the aircraft were spinning or out of control, a knotted rope was installed on the floor from the front of the cockpit to the escape chute.

The first unmanned-captive test flight went off without incident, which was fortunate because it was attended by a level of media attention and exposure beyond anything Dryden and its staff had experienced. After five captive tests and three successful captive-active tests, managers were ready to begin the test program's more difficult free-flight portion.

Researchers expected that the air-launch of the shuttle from atop the 747 would be a high-risk maneuver. There were concerns about the orbiter causing aerodynamic buffeting of the 747's tail and the consequences of an incomplete separation. But the biggest concern was the risk of the shuttle striking the 747 after separation, which could have catastrophic results. Special valves were installed in the Boeing jet to close off the hydraulic lines to the rudder so the rest of the control surfaces would be operable even in the event the tail were lost. Engineers conducted numerous studies, simulations, and wind tunnel tests in attempts to predict the behavior of the two aircraft after separation. But concerns remained.

Finally, Chuck Yeager, who not only had broken the sound barrier with the X-1 but also had flown a French ramjet-powered aircraft off the back of a French transport aircraft, was brought in as a consultant. As veteran NASA pilot Bill Dana remembered it, "Chuck listened politely to [center engineers'] interpretation of the laws of physics and aerodynamics, and then he walked over to a model of the mated 747/shuttle combination and said, 'If you mount the shuttle on the 747 with a positive angle-of-attack difference and get some air flowing between the two, nothing can happen but separation.' So we studied the problem some more and Chuck, of course, was right."[1]



The shuttle Enterprise separates from the Shuttle Carrier Aircraft (a Boeing 747-100) for ALT free-flight no.[1](NASA photo EC77 8608)

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The prototype orbiter Enterprise lands after free flight number 5 on October 26, 1977. (NASA photo EC77 8851)

Time Delay

Indeed, the first four free-flight tests of the shuttle went flawlessly, and launching the orbiter off the 747 was never a problem. The biggest and scariest difficulty encountered during the entire Approach and Landing Test (ALT) program, as it turned out, resulted from a flaw within the orbiter's control system.

The space shuttle orbiters were designed with digital fly-by-wire flight control systems, much like the F-8 digital fly-by-wire system tested at the center a few years earlier. The system worked well in simulations as well as in the first four glide tests of the orbiter, which were conducted at Dryden. But the fifth and final ALT flight was the first in which a landing was attempted on Edwards' paved runway instead of the Rogers lakebed. In addition, NASA pilots flying the shuttle that day, Fred Haise (of Apollo 13 fame) and C. Gordon Fullerton, were attempting a spot landing on the runway to determine whether the orbiter could be landed precisely enough to permit landings at sites other than Edwards. Adding to the pressure on the pilots was the fact that Britain's Prince Charles was on hand to watch the landing, observing from a gazebo near the runway.

The flight marked the first time Haise and Fullerton had flown the orbiter without its tail-cone fairing; they were relying on practice in NASA's Gulfstream II in-flight simulator to help them judge how much to adjust their approach profile. But as was often the case, the simulator performance was not quite the same as that of an actual aircraft, so Haise was flying about 40 knots too fast as the shuttle approached the runway. He deployed the orbiter's speed brakes and was trying very hard to hit the target touchdown spot despite the extra speed.

But with all the stress accompanying the flight, Haise was particularly keyed up, and his control responses were too vigorous. He over-controlled the craft and entered a pilot-induced oscillation (PIO) in two different axes, roll and pitch. The shuttle bounced from one tire to the other before Fullerton finally persuaded Haise to relax pressure on the controls, and the shuttle landed safely.

The incident uncovered a potentially serious problem in the vehicle's control system. In the high-stress environment of actual re-entry and landing from space, pilots could easily get into the same difficulty Haise had, with potentially disastrous consequences.

An aerial view of the Dryden Flight Research Center on 6 November 1979. The ramp has a variety of aircraft present including the Boeing 747SCA, the KC135 modified with the NASA winglets, and the NB-52B mothership. Also visible are the CALSPAN variable stability NC-131 and the original Boeing 747. The structure at the very top center of the photograph is the Mate-Demate Device. (NASA photo EC79 11883)

NASA immediately began a high-priority, agency-wide research effort to identify the cause of the problem and develop a solution. Dryden assigned a flight-controls group to research the issue, and the center's F-8 DFBW aircraft was selected to support the effort. Dryden engineers suspected that the 270-millisecond time delay in the shuttle's fly-by-wire control system was the cause of the problem, so a series of approach and landing tests was conducted, with time delays of increasing duration programmed into the F-8's control system. For safety, the aircraft was equipped with a switch that would turn off the experimental time delay and return the aircraft to its standard fly-by-wire control system.

The F-8 performed well until the time delay reached 100 milliseconds. On that flight, as pilot John Manke was completing a touch-and-go landing and takeoff he entered a severe PIO at a high angle of attack and low airspeed. Hearts stopped in the control room as researchers watched the jet fighter porpoise up and down the runway in increasingly severe oscillations.

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The shuttle prototype Enterprise in Dryden's Mate-Demate Device, being mated to a Boeing 747 modified to serve as the Shuttle Carrier Aircraft. (NASA photo EC77 6576)

Fly-by-Wire Control System

Flight controller Gary Krier quickly directed Manke to turn the time delay off, and Manke managed to regain control of the aircraft and climb to a safe altitude. But it was a close call. Researchers estimated that had the oscillation gotten any larger, Manke would have stalled and lost the airplane. Even after Manke gained a little altitude, the control room engineers sat in stunned, relieved silence. Finally, Krier keyed his microphone again and said, "Uh, John? I don't think we got the data on that – we'd like to have you run that one again." Laughter erupted, breaking the tension.2

Clearly, there was a critical threshold in the time delay of a fly-by-wire control system. One solution would have been to redesign the orbiter's control system, but that would have seriously delayed the shuttle's development and deployment. Fortunately, Dryden researchers were able to not only diagnose the problem, but also come up with an alternative solution. They designed a suppression filter for the outer loop of the control system that would correct the problem without forcing any changes to the basic control laws. The filter was installed and is a permanent fixture in the shuttle fleet, which has accumulated an exceptional record for landings. A second result of the Dryden F-8 shuttle research was that the military added a specification for all future fly-by-wire aircraft, limiting control system time delays to less than 100 milliseconds.

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Gunman F-14A #991 in flight on September 5, 1980. This aircraft was used in aileron-rudder interconnect (ARI) research, which showed that the ARI control laws significantly improved controllability of the F-14 in spins, although they were not incorporated into the F-14's digital flight control system until the D-model in the 1990s. Langley Research Center engineers developed the control laws, which Dryden flight-tested in partnership with Grumman and Honeywell. (NASA photo EC80 13630)

For a short time after the glide tests and control system research flights, Dryden's efforts in support of the shuttle program lessened. But the shuttle – and the world's attention – returned to Dryden in April 1981 when pilots John Young and Robert L. Crippen landed the orbiter Columbia at Edwards after the first space shuttle mission. Dryden continued to support shuttle missions through ground support of landings and with its three-story, steel Mate-Demate Device (MDD), used to mount and remove the shuttles from the two modified Boeing 747 carrier ships. In 1993 – in part because of research conducted by pilots at Dryden – the Kennedy Space Center in Florida became the primary landing site for the shuttle program. But Edwards, and Dryden, continue to play an important role as a backup landing site if weather in Florida is not conducive to a safe landing there.

Safety

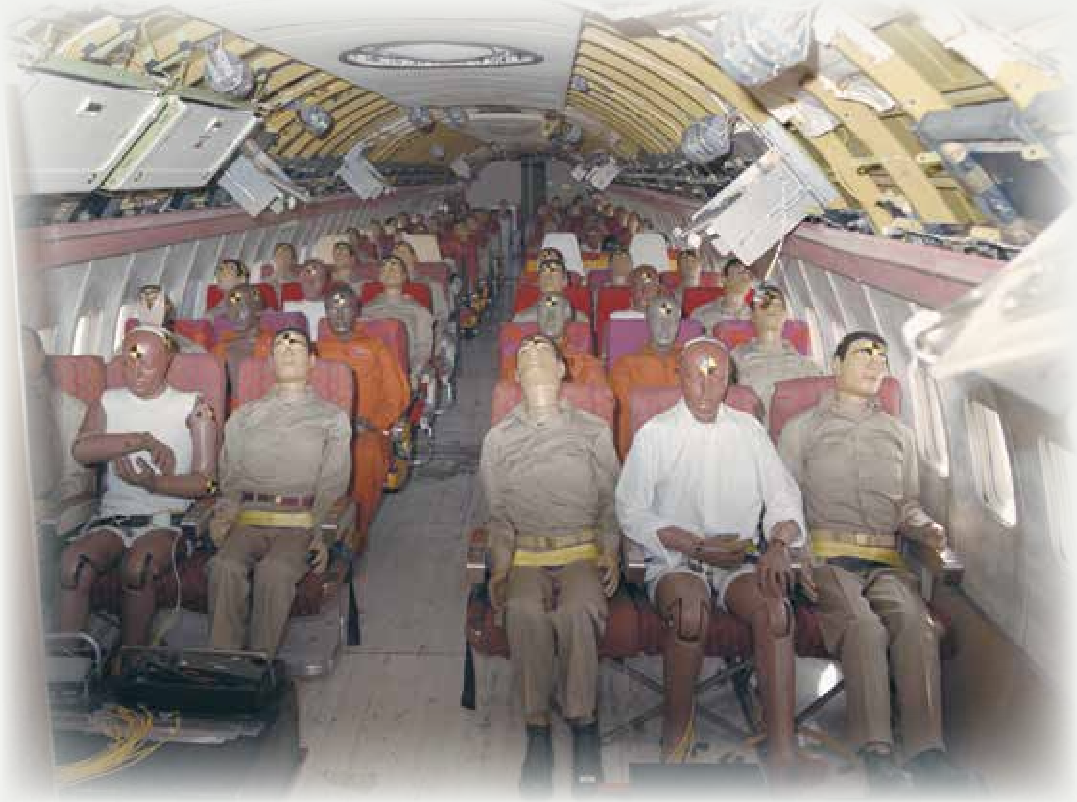
In addition to analyzing potential problems in new spacecraft like the shuttle, Dryden, in its fourth decade, continued work on improving the safety of craft flying within the Earth's atmosphere. In the late 1970s, Air Force officials wanted to explore ways to improve the unusual ejection system of the F-111 Aardvark fighter-bomber. In contrast to many fighter designs in which pilots and crewmembers ejected from a troubled craft in individual ejection seats, the F-111 had been designed to have the entire cockpit eject from the rest of the airframe. The crew escape pod, as it was called, was then lowered to the ground by parachute. The Air Force, however, was concerned about the speed at which the crew capsule hit the ground. It was also interested in extending the life of the F-111 capsule parachutes. Dryden's B-52 launch aircraft offered the Air Force a way to explore the problem safely. Between 1977 and 1995, Dryden and Air Force researchers carried out four series of experiments to explore ways to decrease the velocity at which the F-111 cockpit pod hit the ground and to extend the life of the parachutes.

Aircraft 9Safety

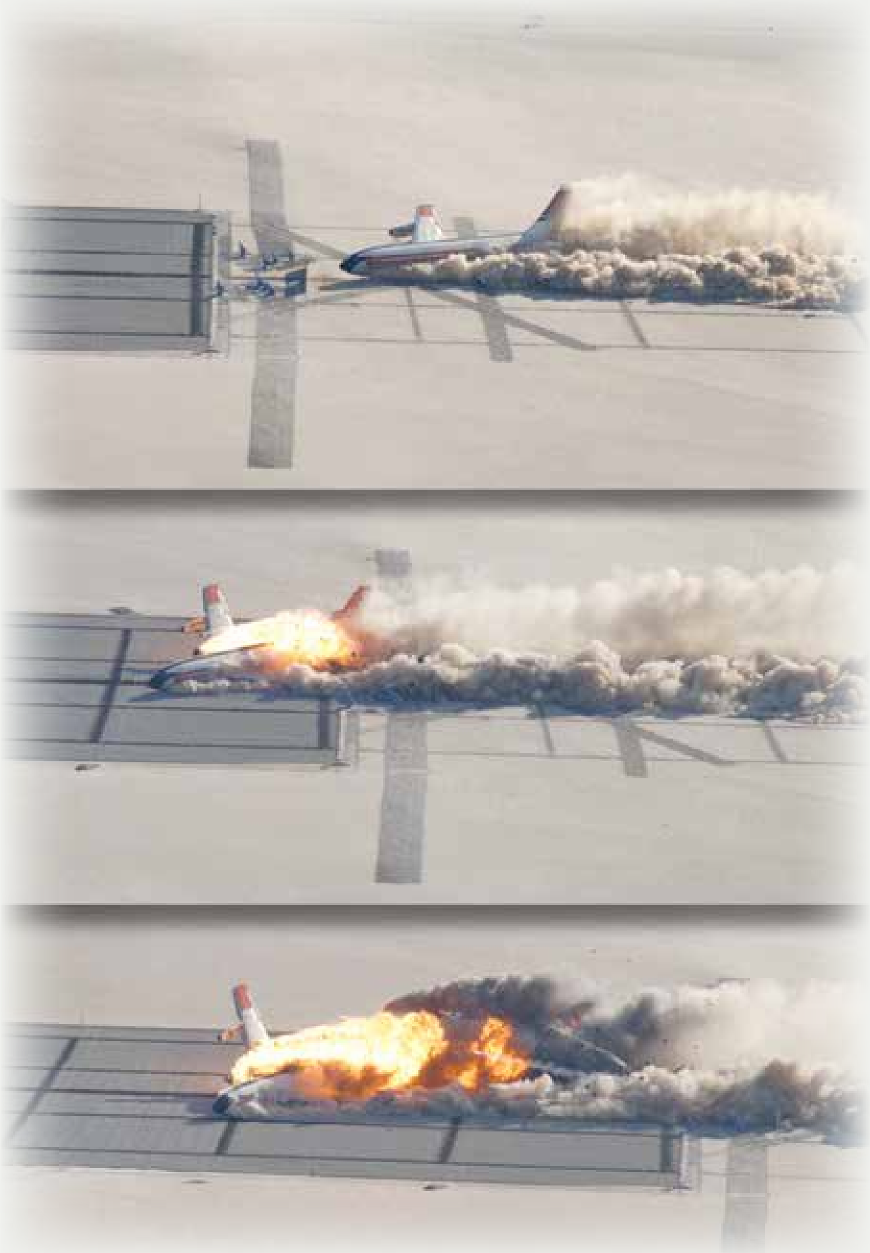
In the early 1980s, Dryden's assistance was sought again after the Navy lost several Grumman F-14 Tomcat fighters in spin incidents. The F-14 was having engine difficulties at high angles of attack, and if one engine suffered a compressor stall or flamed out, the asymmetric thrust from the remaining engine had a tendency to send the plane into a spin. The Tomcat had a flat spin mode that was proving very difficult to recover from and had resulted in the loss of several crews and aircraft.

Navy officials asked Grumman to look into the problem, and Grumman enlisted NASA's help in developing a solution. Working with Grumman, engineers at Dryden and Langley came up with a new control law involving what is known as an aileron rudder interconnect (ARI), which they hoped would decrease the aircraft's susceptibility to spins and departures from controlled flight. The new control law was tested extensively in simulators before being gingerly explored in flight with an F-14 loaned to Dryden for the research.

The flight tests showed that the new control law did, in fact, decrease the F-14's susceptibility to spins. Unfortunately, budget constraints prevented the Navy from applying the update to fleet F-14s until the late 1990s. Eventually, however, the new control laws were incorporated into the digital flight control systems of the F-14D production models, greatly decreasing the danger of spins and improving the safety margin for F-14 pilots in high-angle-of-attack conditions or during slow-speed maneuvers.



Crash dummies serving as instrumented simulations of passengers on the Boeing 720 used in the Controlled Impact Demonstration. (NASA photo EC84 29510



This sequence of photos shows a remotely piloted Boeing 720 airliner approaching and striking iron posts embedded in the lakebed, then bursting into flame. This Controlled Impact Demonstration showed that anti-misting kerosene did not prevent fuel fires during airplane crashes. (NASA photos EC84 31805, EC84 31806, and EC84 31807 in the order shown)

In addition to its work with military aircraft safety, Dryden also continued work on civil aviation safety projects, including a memorable research effort with the Federal Aviation Administration in 1984. The FAA was evaluating an anti-misting jet fuel additive known as Anti-Misting Kerosene, or AMK, that seemed capable, at least in laboratory testing, of preventing fuel fires in airplane crashes. The concept seemed so promising, in fact, that the FAA was preparing to publish a Notice of Proposed Rule Making (NPRM) as a first step toward requiring the additive in certain types of jet aircraft.

Before proceeding with the NPRM, however, the agency wanted to test the additive in actual crash conditions. The center's desolate surroundings and experience with remotely piloted vehicle research (in addition to the 3/8-scale F-15, it had flown other remotely controlled craft over the years, including small motherships, the Hyper III, and a small oblique wing RPRV) made it a logical support resource for such an experiment. Dryden engineers rigged an old Boeing 720 jetliner with remote controls, fueled it with Jet A mixed with AMK, and guided it to a controlled crash landing on the lakebed. Iron posts had been set up to ensure that the fuel tanks would be ripped open upon impact, since that was the scenario most likely to result in a post-crash fire. The experiment was called the Controlled Impact Demonstration (CID), and the FAA expected for it to be a relatively tame event.

Those expectations proved wrong. In one of the center's most dramatic moments of discovery, the remotely piloted 720 descended onto the desert floor .and exploded into a staggering inferno. Needless to say, FAA plans to require the fuel additive were discontinued, and from that point forth, Dryden researchers referred to the CID experiment as the *"Crash in the Desert."* Nevertheless, the flight experiment was a stark illustration of why flight research is such a critical step in technology development. The fuel additive had worked well in laboratory testing. But it was a monumental failure in the real-world environment of an actual airplane crash.

Research into safety improvements for operational aircraft was never the center's primary focus. But Dryden was well suited for the work. For one thing, the daily requirements of keeping research aircraft flying meant that Dryden's staff was already experienced in troubleshooting aircraft and devising practical test methods and solutions. Engineers prided themselves, in fact, on their ability to troubleshoot aircraft and find quick solutions to operational problems. They knew how to rig a jetliner to be flown by remote control or develop a test program to evaluate problems in a fly-by-wire control system. They could design a research effort to safely investigate aircraft characteristics that had killed pilots. And they possessed the enthusiasm and creativity to pursue these projects successfully.

The various safety efforts undertaken at the center also benefited greatly from the technical agility that was so pervasive at Dryden. Troubleshooting of projects tended to materialize suddenly when an aircraft program or proposed modification ran into difficulty, requiring quick action and quick answers. But since Dryden has always had to juggle different programs, and switch gears and priorities quickly, the center could accommodate unexpected efforts with tight deadlines. Indeed, Dryden's flexibility and its talent for practical and effective troubleshooting remain two of the center's greatest strengths, even today.

Efficiency/Performance

At the same time Dryden engineers and pilots were working on shuttle testing and safety research, the center also was involved in experiments designed to identify ways of improving the efficiency and performance of both military and civilian aircraft. Some of those experiments involved physical changes to wings or configurations, while others involved advances in aircraft internal systems.

Winglets

Among experiments flown at Dryden in the late 1970s was one that examined the use of winglets – small, nearly vertical fins installed on an airplane's wingtips to help reduce the drag caused by vortices swirling off the end of the wing. In the late 1960s and early 1970s, Dryden looked at the impact of wingtip vortices on other aircraft flying in trail. But now, as part of a larger effort to improve the fuel efficiency of transonic aircraft, researchers were examining ways to decrease the drag of the vortices themselves.

The wingtip concept actually dated back as far as 1897, when an inventor took out a patent on the idea. But it was not until Richard Whitcomb, the engineer who also had envisioned the supercritical wing, began a focused investigation into winglet aerodynamics that the concept evolved into an applicable technology. Coincidentally, winglets are usually supercritical airfoils. Whitcomb tested several designs in the wind tunnels at Langley and then chose the best configuration for a flight research program at Dryden.

Winglets were installed on a KC-135A tanker on loan from the Air Force and flight tested in 1979 and 1980. The research showed that the winglets could increase an aircraft's range by as much as seven percent at cruise speeds, a significant improvement. The first industry application of the winglet concept was in business jets, but winglets are now incorporated into most new commercial, business, and military transport aircraft, and are offered as aftermarket retrofits on those aircraft that left the factory without them.

Oblique Wing

A more radical approach to improving a wing's efficiency also was explored at Dryden during the late 1970s. Called the *"oblique wing,"* the concept involved a wing that pivoted laterally up to 60 degrees around a center point on top of the fuselage. At higher speeds, aligning the wing more closely with the direction of flight reduced drag significantly. Robert T. Jones, the NASA Ames researcher who pioneered the concept, had analyzed the idea on paper and in wind tunnels and predicted that a transport-size aircraft with an oblique wing, traveling at 1,000 miles per hour, might be twice as efficient as a conventional aircraft and might also create a milder sonic boom.

Oblique Wing

To test the concept in flight, Ames and Dryden researchers proposed building a low-cost, piloted vehicle that could first explore the flight mechanics of an oblique wing at low speeds. If the results from those flights were encouraging, they planned to pursue funding for a higher-performance research aircraft capable of flying in the transonic range.

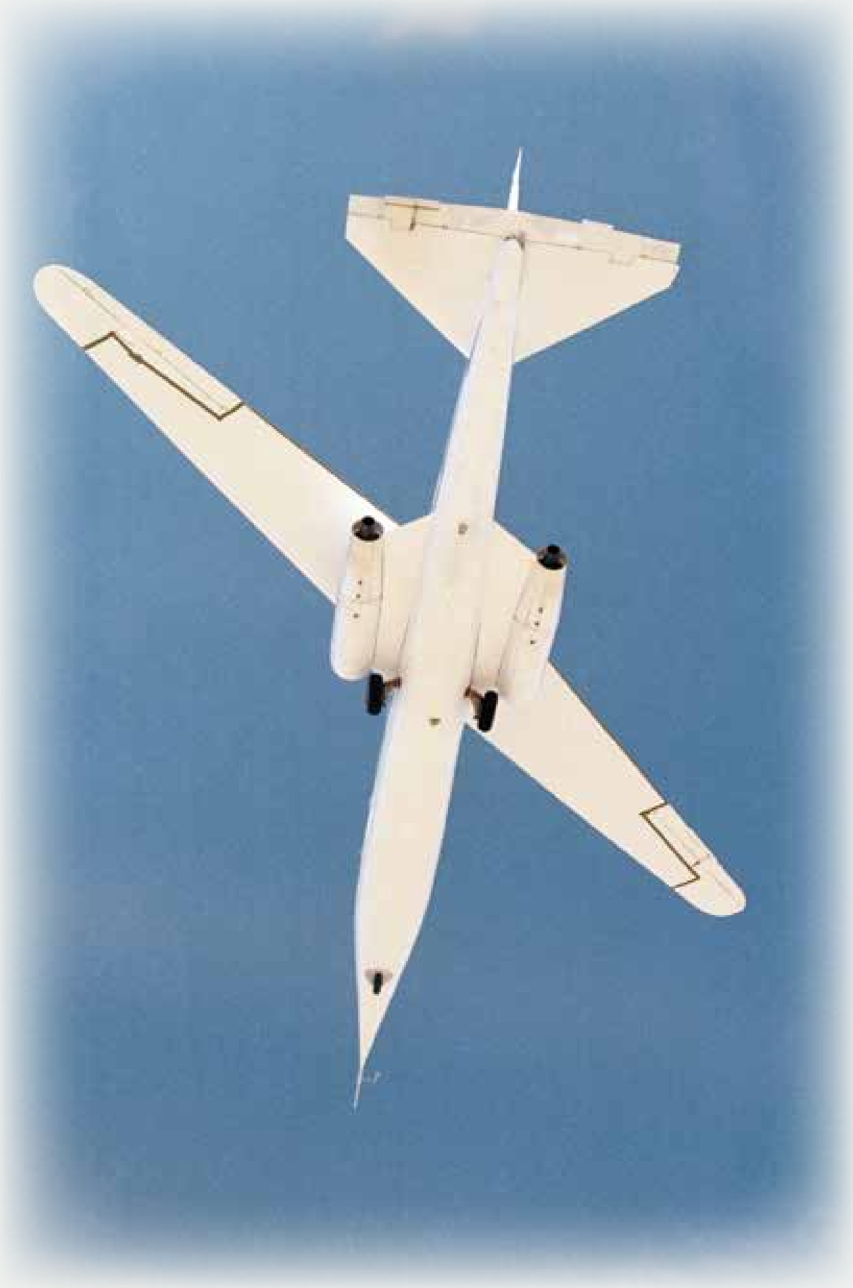
In 1977, construction began on the low-speed AD-1, so named for the Ames and Dryden research centers co-sponsoring the research effort. The AD-1 was a twin-engine, jet-powered composite aircraft designed by engineers at Ames, Dryden, and the Rutan Aircraft Factory in Mojave, California, and built by the Ames Industrial Company. Kept perpendicular to the fuselage for takeoff and landing, the wing was then pivoted up to 60 degrees for the higher-speed portions of the flight. It was a simple vehicle with a simple price tag; it had un-augmented controls and a top speed of only 175 knots, and its entire design and construction cost less than $300,000.

The aircraft flew 77 research flights between 1979 and 1982 (and one demonstration flight at the Experimental Aircraft Association's annual meeting at Oshkosh, Wisconsin), demonstrating satisfactory handling qualities through a 45-degree angle of wing sweep and acceptable qualities at up to 60 degrees wing pivot configuration. It even performed three landings with the wing pivoted 45 degrees. A larger, faster version has yet to be built, and the concept has yet to be incorporated into any production aircraft. But the research provided engineers with valuable information about a potential new configuration and approach for making aircraft more fuel efficient. It also demonstrated once again the aggregate benefits of a simple, low-cost aircraft and flight research effort.

Laminar Flow Research

Another way to increase the fuel efficiency of aircraft was through the use of laminar flow airfoil designs. *"Laminar flow"* is an airflow that smoothly follows the contour of an airfoil and whose layers of air do not mix. Because laminar airflow generates less drag, it can make aircraft more fuel efficient, giving them either longer range or greater payload capacity.*

Laminar flow designs actually date to World War II. The P-51 Mustang, for example, was known for its highly efficient, laminar flow wing. But even the P-51's wing achieved laminar flow for only a very short distance from its leading edge. Maintaining laminar flow across any significant section of a wing was a more difficult problem to solve. As fuel efficiency became a higher priority in the 1970s, however, finding ways to increase the amount of laminar flow across a wing became a higher research priority.



The Ames-Dryden-1 (AD-1) aircraft in flight on July 9, 1980, with the wing pivoted. (NASA photo EC80 13303)

In the late 1970s, Dryden and Langley researchers began conducting laminar-flow experiments that examined potential solutions to the problem. The first research effort looked at natural laminar flow (NLF), or modified wing designs that could increase the amount of laminar flow without any additional systems or hardware. Dryden engineers first bonded an extremely smooth NLF airfoil glove onto the center's F-111 TACT research aircraft, to see how various angles of wing sweep might affect laminar flow. Those research flights were followed by similar experiments with a Navy F-14 Tomcat. The Tomcat also had a variable-sweep wing, but it could be used to investigate higher sweep angles than those of the F-111.

Both of those flight research projects gave researchers valuable information on how much sweep could be incorporated into a subsonic wing before it began to lose its laminar-flow properties. The research also provided data on the influence of other factors on subsonic laminar flow, ranging from the speed of the aircraft to the effects of bugs splattered on a wing's leading edge.

Laminar Flow Research

At the same time, Dryden engineers began exploring the concept of active laminar flow, through which some artificial means is employed to keep airflow moving smoothly over an aircraft wing. Active laminar flow held great potential for increasing the efficiency of both subsonic and supersonic aircraft, since laminar flow does not occur naturally at supersonic speeds on aircraft with highly swept wings. Dryden's first experiments in active laminar flow control, however, were in the subsonic range, using the center's four-engine Lockheed JetStar business jet.

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The Lockheed JetStar aircraft flies a flow-visualization mission on June 14, 1978. (NASA photo ECN 33222-7)

The JetStar experiments entailed bonding two kinds of skins, one perforated and the other slotted, on the aircraft's wings and then using a turbo compressor to draw air through the perforations in order to keep air flowing smoothly along the contours of the wing surface. The JetStar flew simulated airline operations in various areas around the country to investigate the impact of such factors as weather and bug strikes on laminar flow. The equipment required for the JetStar system was too heavy to allow the approach to be practical for any operational, subsonic aircraft. Nonetheless, Dryden's JetStar research proved the feasibility of the active laminar flow concept and laid important groundwork for the center's later research into more advanced active laminar-flow control systems on supersonic aircraft.

Integrated Digital Control

Some of the most significant work done by Dryden in its fourth decade, however, continued to be its research into the merging of computer and aircraft technologies. The center's work with the F-8 Digital Fly-By-Wire aircraft and Digital Electronic Engine Control (DEEC) in the early 1970s had proven the feasibility of relying on computerized flight and engine controls. The next step, however, was to look at ways the two technologies might be integrated to enhance aircraft safety, performance, and efficiency.

One of Dryden's F-15s flies on February 24, 1978. This aircraft was used in propulsion, buffet, base drag, and shuttle tile studies from 1976 to 1983. (NASA photo EC78 9319)

Integrated Digital Control

One of the first projects to explore the potential benefits of an integrated, computerized flight and engine control system involved the center's Lockheed YF-12C– actually the famous SR-71 Blackbird spy plane. Because of the aircraft's unique flight environment, the Mach 3-capable Blackbird was a challenge to control in terms of both its flight path and its complex engine-inlet management. At supersonic speeds air striking the mouth of the engine inlet developed a shock wave. As speeds increased the spike moved fore or aft in the inlet to control where that shock wave sat. The goal was to move that shock wave into the engine inlet and keep it there. Unstarts were triggered by a number of factors but invariably resulted in the supersonic shockwave jumping outside the inlet; they were violent and potentially dangerous events that led to the loss of more than one of the multi-million-dollar aircraft. Most of the time, the spike system worked well. But the Blackbirds had experienced frequent problems with this phenomenon in part because modulation of the system was insufficiently precise.

In the foreground YF-12C #937 flies safety chase for YF-12A #935 on August 7, 1975. An F-104N leads the formation in preparation for the cold wall test. The YF-12C, actually an SR-71, later was used in flight research on a computerized system that integrated the aircraft's inlet control, autothrottle, air data, and navigation functions to help prevent a condition known as "unstart." (NASA photo EC75 4774)

To see if a computerized system could improve the YF-12's performance and reduce its trouble with unstarts, Dryden researchers designed a system that integrated the aircraft's inlet control, auto throttle, air data, and navigation functions. Flight research with the system began in 1978. The integration was not optimized, but it did result in dramatic performance improvement. By improving coordination among those functions, the system increased the aircraft's range by seven percent. More important, the precise inlet management was successful in reducing the incidence of unstarts. The improvements demonstrated by Dryden engineers with the aircraft's integrated control system were great enough, in fact, that the system was retrofitted into the entire SR-71 Blackbird fleet as part of a 1983 avionics upgrade.

The YF-12 experiments also generated additional interest within both NASA and industry in digital engine control and integrated control concepts. The engine manufacturer Pratt & Whitney had designed a digitally controlled engine, but Air Force officials felt that the technology was still too high-risk to fund it as a production concept. So Pratt & Whitney approached Dryden and asked if the center would consider a joint flight research program to help mature the technology. Dryden accepted, and Pratt & Whitney's engines were installed on an F-15 fighter Dryden had obtained from the Air Force in 1976.

Dryden and Pratt & Whitney engineers conducted flight research with the re-engined F-15 from 1981 to 1983. The flights identified several problems with the engine design, which Pratt & Whitney was then able to fix. But the flight research also conclusively showed the technology's potential. The digital electronic engine control engines allowed stall-free engine performance throughout the F-15's flight envelope and faster throttle response, improved air-start capability, and increased afterburner capability by an additional 10,000 feet of altitude. The results were impressive enough that the Air Force committed to full-scale development and production of what became the F-100-PW-220/229 engine. Pratt & Whitney also applied the Full Authority Digital Engine Control (FADEC) technology to its PW-2037 commercial turbofan engines, which were incorporated into Boeing's 757 transport aircraft. Clearly, the research effort had been a significant success. In fact, both the Air Force and Pratt & Whitney credited Dryden's F-15 DEEC research program with advancing the introduction of DEEC technology by one and a half years and saving approximately $42 million.[3]

Adaptive Engine Control System

Following the DEEC research, Dryden engineers wanted to continue exploring technology that could integrate engine and flight control systems. The result was the Highly Integrated Digital Electronic Control (HIDEC) program, which was implemented with the same F-15 aircraft used in the original DEEC research. For the HIDEC program, Dryden engineers modified the fighter not only with digital engine control technology, but also with integrated digital flight and engine control systems.

The first research conducted with the HIDEC aircraft was the Adaptive Engine Control System (ADECS) program. The concept behind ADECS was that conventional engine operation had to be based on a worst-case scenario of what an aircraft might be doing. If an airplane were at a very high angle of attack, for example, airflow into the engine would be irregular. So the engine parameters had to be set so the engine would not experience a compressor stall in that configuration. Unfortunately, that also meant that when the aircraft was in straight and level flight, the engine was operating at those same parameters even though the engine was far above its stall margin, leading to significant inefficiencies. By integrating the flight control and air data systems of the HIDEC aircraft with electronic engine controls that adjusted the engine exhaust nozzles, researchers could adjust the operation of the engine to suit the varying flight conditions of the aircraft.

McDonnell Douglas F-15A #287 Digital Electronic Engine Control aircraft is on the Dryden ramp with its engine on a cart. (NASA photo EC81 16382)

The ADECS flight research showed that integrating the controls could reduce engine temperature while holding engine thrust constant, which could extend the life of the engines by as much as 10-12 percent. It also could increase the thrust of the engines by 8-10 percent, allowing an increase in climb rate of 10-25 percent or a reduction in fuel consumption of 7-17 percent. Those results improved even further in a follow on HIDEC research effort known as Performance Seeking Control (PSC). In the PSC effort, the set tables on which the ADECS had relied for adjusting engine parameters were replaced with more accurate, real-time engine and aircraft sensors on board the aircraft. In addition, the PSC technology added control of the F-15's engine inlet ramps to the system's integrated elements. These changes led to an additional 3-5 percent increase in thrust over that of the ADECS technology.

As a result of the HIDEC flight research, Pratt & Whitney decided to incorporate integrated control system technology into its Increased Performance Engines, as well as the engines designed for the YF-22 Advanced Tactical Fighter technology demonstrators, which evolved into the Air Force's F-22A Raptor. But the technology advances tested in the HIDEC program were just the beginning. Researchers and design engineers continue to explore and find new and better ways of integrating aircraft controls to achieve more efficient, safe, and capable designs.

McDonnell Douglas F-15A #287 performs Digital Electronic Engine Control flight research on June 23, 1981. (NASA photo EC81 15815)

Aerodynamic Truck Fairings

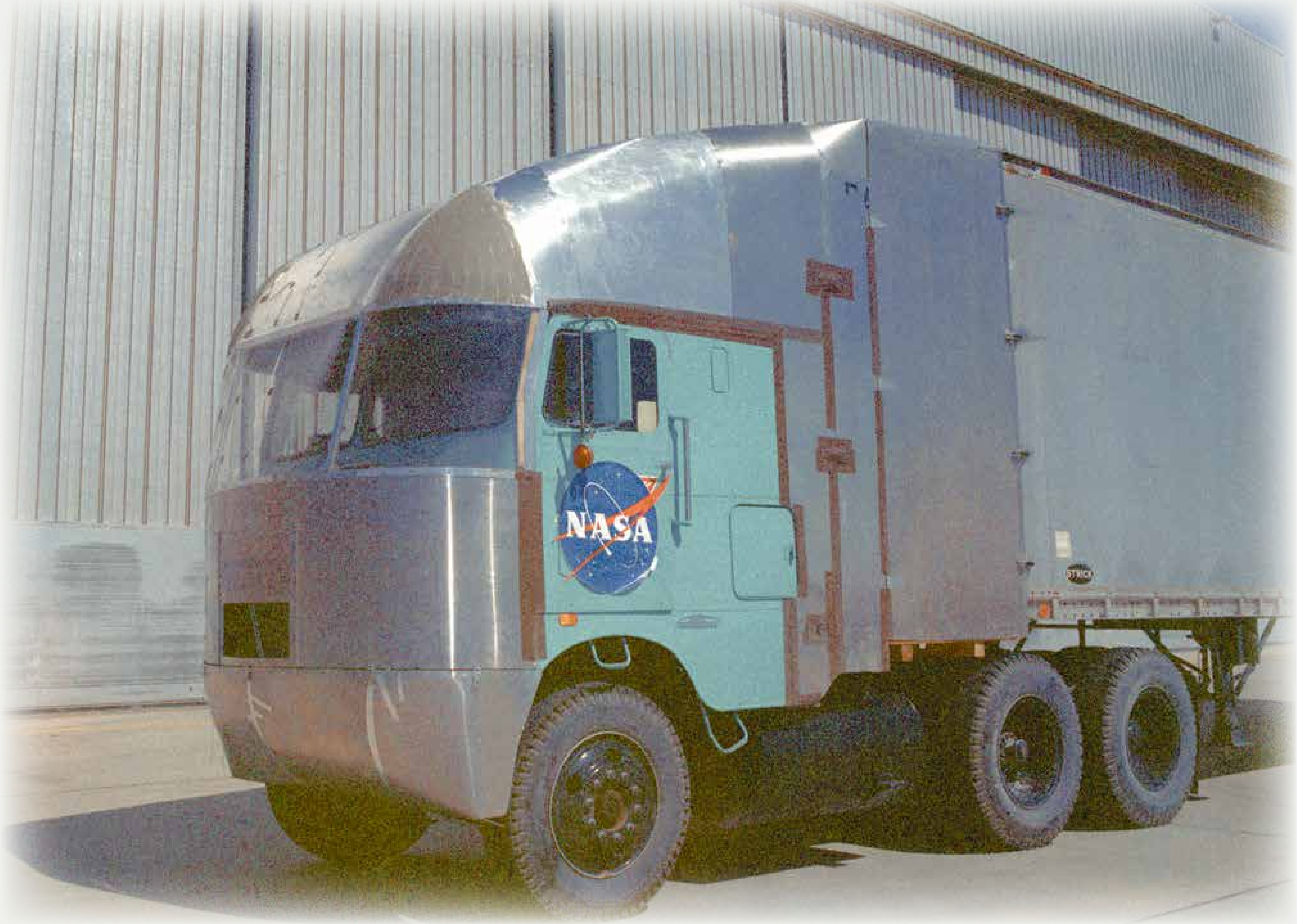
In one of the more unusual contributions the center has made to efficiency, an engineer in 1973 began research on the aerodynamics of commercial vehicles. The efforts were linked to the gas crisis the country was undergoing at the time – and his own experience riding a bicycle to work along a busy two-lane freeway frequented by semi tractor-trailers. A passing truck, noticed Ed Saltzman, the engineer, pushed a wave of air ahead of it that tended to drive him off the road and into the sagebrush. The truck's wake, on the other hand, was powerful enough to suck him back into the lane of traffic. Being an aerodynamic engineer, he knew well the drag penalty associated with a blunt-tailed object moving through the air, and he wondered if there was a way to mitigate this on trucks.

With the center director's blessing, he began a small project to establish the baseline drag of an old mail delivery van at the center. Saltzman's team boxed in the van with aluminum so that it resembled a shoebox, quite literally. Knowing the drag associated with such a shape and size allowed them to determine the vehicle's aerodynamic drag, and to separate it from mechanical and rolling drag so they could measure changes in aerodynamic drag only. With this in hand the team began modifying the shoebox shape to see what changes improved the vehicle's aerodynamics. Rounding all four front and rear edges and corners yielded a reduction in drag of 52 percent, while sealing the bottom of the vehicle yielded another 7 percent drag reduction. The engineers estimated the potential gain in fuel economy at between 15 and 25 percent at highway speeds.

Word about this research spread and before long the U.S. Department of Transportation asked the center to conduct research on five after-market products being sold to truckers with promises of significant fuel mileage improvements. And so the team began another experiment: after establishing the baseline drag of a leased tractor-trailer unit, they attached each of the add-on fairings, and conducted a series of tests to see which product had the greatest benefit. The best of the add-on products reduced the drag by 16-24 percent, depending on road and weather conditions, for a fuel mileage improvement of roughly 10 percent.

By the time they published their results the engineers had come up with some ideas of their own for the truck, which they put into motion. Using their experience with the shoebox they designed a fairing for the rented cab-over tractor. The fairing not only smoothed all the corners of the blunt truck, but directed airflow around, under, and up over the cab. Recognizing that the gap between tractor and trailer was a source of tremendous wind turbulence, and hence, drag, they sealed it off as well, hinging the fairing at the cab and putting rollers on it where it met the trailer's side so that the cab could make turns and not break the new structure.

The highly modified aerodynamic truck and trailer combination took to the road for a series of tests that revealed a drag reduction of 37 percent and a gain in mileage of between 20 and 24 percent. Again, the results were published, and members of the commercial trucking industry began paying attention. Within a decade the first of a new generation of tractors appeared on the road, tractors that were shaped in wind tunnels to be as low-drag as possible.



The modified aerodynamic tractor-trailer used in the truck drag reduction study. It was modified according to designs at the center." (NASA photo EC75 4724)

The HiMAT

What Dryden engineers discovered along the way, beyond how to reshape a blunt road vehicle to make it more aerodynamic, was that maximum drag reduction could only be achieved by reshaping both the front and rear of the vehicle. This is easier done with cars than long-haul trucks, whose boxy shape is largely determined by their purpose. Nevertheless, much of why over-the-road commercial trucks look the way they do now stemmed from this important work at Dryden during the mid 1970s and 1980s.

HiMAT

In addition to advances in computer technology, the 1970s also saw vast improvements in aircraft construction materials. Composite materials, which are often used today to build entire aircraft, were just beginning to find their way into new, experimental designs. Composites are lightweight and far more adaptable than metal to unusual curves and designs, while offering a high degree of unidirectional stiffness and strength. As a result, the advent of reliable composite materials – especially when combined with computerized flight and engine controls – opened the door to a whole new world of aircraft configurations. And in the late 1970s, military interest in exploring new configurations was increasing, particularly with regard to configurations that might give aircraft better maneuverability.

In the 1950s and 1960s, the driving design objective of military fighter aircraft was speed. Speed was life, and fast entry into and exit from a combat area was thought to provide the best combat edge for a fighter pilot. In the post-Vietnam era, however, that thinking began to change. The American fighters in Vietnam had found themselves outmatched in close-in combat, where maneuverability was more important than speed alone. And as the military looked to Cold War threats in Europe, where Soviet and U.S. bases were separated at times by only a few miles, a fighter pilot could find himself in close-in combat almost as soon as he took off. So maneuverability replaced speed as the driving priority for military fighters.

These two forces – advances in computers and materials coupled with the military's interest in more maneuverable aircraft – merged in the late 1970s in a Dryden research effort known as the Highly Maneuverable Aircraft Technology (HiMAT) program. The HiMAT vehicle was jet-powered and remotely piloted, and incorporated numerous advanced design features, including a computerized flight control system, a canard, a swept wing, and graphite-and-fiberglass composite construction.

Dryden research pilot Bill Dana concentrates in a flight simulator for the Highly Maneuverable Aircraft Technology (HiMAT) airplane in preparation to fly the HiMAT remotely from a ground cockpit. (NASA photo EC79 10925)

The HiMAT vehicle was approximately half the size of a production fighter and was launched from the same B-52 mothership that had carried the X-15s and the lifting bodies. Due to its remote operation and light wing loading, it could perform maneuvers that piloted, production fighters couldn't, such as sustained 8-g turns at an altitude of 25,000 feet and a speed of Mach 0.9. An F-16, by comparison, could sustain only about 4.5 g's in similar flight conditions.

The two Rockwell International HiMAT vehicles had a top speed of Mach 1.4 and were flown 26 times between 1979 and 1983. Because of its ability to sustain high-g turns at high speeds, the HiMAT vehicle could execute turns almost twice as tight, and therefore do it almost twice as fast, as operational fighters. The design also convincingly demonstrated the ability of composite construction materials to provide adequate stiffness and strength when used in an aircraft structure.

Budgets and National Priorities

Like the HIDEC research, the HiMAT program was only the first step in exploring new and more maneuverable aircraft configurations. As it was, the HiMAT program provided manufacturers with a much greater confidence in composite construction materials. But it also sparked researchers and designers to imagine other configurations and other methods that might improve the maneuverability of an aircraft. In particular, the HiMAT research strongly influenced the design of a piloted research aircraft that, in Dryden's fifth decade of operation, would go much further in exploring and demonstrating advanced design technology. That aircraft was Grumman Corporation's ground-breaking X-29 – an aircraft that was only one of several at Dryden in the 1980s and 1990s that picked up where the HIDEC F-15 and the HiMAT remotely piloted vehicle left off and journeyed into areas of aircraft configurations, propulsion, and operation that were nothing short of revolutionary.

HiMAT PROJECT
TEAM
LAST FLIGHT
JAN.12,1983
DRYDEN
HiMAT

Both Highly Maneuverable Aircraft Technology (HiMAT) airplanes were aligned on Rogers Dry Lake on January 12, 1983, after the last flight of the project. (NASA photo EC83 10925)

The Dryden Flight Research Facility

Significant research was still being done at Dryden in the 1970s and 1980s, and the center was still making valuable and tangible contributions to industry and the nation at large. But the center's future was still uncertain, as indeed it had been since the advent of the space age. When the cutting edge of research and technology was still an aircraft – albeit a rocket-powered, supersonic aircraft like the X-1 – a center that specialized in advancing aeronautical technology made sense. And the higher-speed aircraft clearly pointed to the need for a research base in an open and remote location such as Dryden's.

But as the nation's focus shifted to space, as transport aircraft stabilized in both configuration and in speed, and as the military's output of new, cutting-edge fighter aircraft decreased, it was harder for outsiders to see the value in a place like Dryden. Starting in the early 1960s, the center's management found itself defending the value of the contributions it was making and could continue making. The issue was simply one of budgetary restrictions, which perennially produced intense pressure at NASA to re-examine the agency's allocation of scarce resources. It is a dilemma that continues to the present, and one that has given rise to recurring bouts of expansion and retrenchment within Dryden. Work at the center continues, but it is conducted amid an ever-shifting landscape of budgets and national priorities.

At first, the pressure was the shift in budgetary priorities to space, though even as Neil Armstrong stepped onto the moon's surface, NASA faced pressure to decrease its large, Cold War-driven budget. Even the space side of NASA faced budget cuts. The space shuttle program injected purpose and funding into NASA's follow-on space exploration programs, but Dryden still was viewed primarily as an aeronautical research center. And a center that contributed materially to a dozen critical advances in aeronautical technology was harder to sell than the control or launch center for a huge, public, national program like the shuttle program.

Conclusion

There have been various efforts to clarify Dryden's role throughout the years; at least three times, NASA has tried to consolidate aircraft flight testing to one center. But with several aeronautical centers in the agency's structure, each with political allies, a long history, and fierce determination to retain an onsite flight element, none of those efforts succeeded entirely. At the same time, the center has periodically been in danger of being downsized or even closed under some restructuring plans or new agency administrations. The bottom line is that to work at Dryden is to work in a place that does not, in the end, control its own destiny. This fact of the center's life was driven home acutely in 1981, when the center was abruptly told that it was to be merged with the Ames Research Center. The Dryden Flight Research Center would henceforth be known as the "Ames Research Center, Dryden Flight Research Facility."

The move was an effort on the part of NASA management to cut costs by merging two of its smaller aeronautical research centers – Dryden and the Wallops Island Flight Center – into the larger research centers of Ames and Goddard, respectively. In theory, the plan would eliminate one layer of management and allow some consolidation of resources. In the case of Dryden, however, the plan actually generated more bureaucracy and friction than it did away with. All research plans had to be cleared through Ames first, and then through NASA Headquarters. Having most of the administrative management located off-site created other problems. It was 300 miles between managers at Ames, in the San Francisco Bay area, and researchers at Dryden, and frustrations in communication abounded. Morale at Dryden plummeted.

Yet while the situation may have seemed bleak to Dryden employees at the time, the truth was that the center had been adapting to change since its inception, and this was simply another twist in a road that had never been predictable or straight. The good news was that Dryden's staff once again moved to keep pace with the changes, joining forces with industry and the military to produce the highly successful HIDEC and HiMAT research efforts – not to mention a host of other important projects that followed those two. And if the Dryden workforce could have seen a little farther into the future, it would have rested easier, for Dryden's path continued to turn. Thirteen years after Dryden was stripped of its center status the winds shifted again and center status was restored, proving once again that the only constant at Dryden – as with the world and technology itself – was change.

By the mid-1970s, Dryden had established itself as a research center for far more than just high-speed, or even atmospheric, flight. It had branched out into space applications and improvements in the safety, efficiency, and performance for a wide variety of both space and aircraft. The center's research focus had changed in other ways as well. Although new experimental air and spacecraft configurations looked more spectacular to the outside observer, some of the most valuable work undertaken at Dryden in the 1970s focused on less visible changes to internal aircraft systems. Computer technology was revolutionizing the internal workings of air and space vehicles, and the system improvements that technology allowed would, in time, fundamentally change what aircraft could look like and accomplish, as well as how they could be flown.

The center's experience and resume´ were diversifying. And that was a good thing, because the world was changing as well. To remain relevant, and to maintain its ability to meet the expanding and diversifying needs of industry and the nation, Dryden was going to have to do more than just conduct valid research. It was going to have to change with the times and learn to support new relationships, new research areas, and new organizational structures. For many researchers at Dryden, adapting to all the changes in funding, priorities, and organization was undoubtedly harder than the engineering challenges posed by flying Mach 5. But the two came hand in hand. Research took money and partners as well as talent and bright ideas. So while no one at Dryden was happy about losing the status of an independent center, employees once again sighed, rolled up their shirtsleeves, and dug into the work at hand – work that would make important contributions to aircraft safety and performance... and lead them into realms where no aircraft had gone before.

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Chapter 6

New Ways,
New Partners

AAW Test Flight Over Dryden
by Robert F. Goetzl

A GE F404 jet engine undergoing maintenance in Dryden's engine shop. Virtually all of the center's aircraft engines pass through - for overhauls, inspections, and maintenance. (NASA photo ED06 0046-05)

Dryden's Fifth Decade

Despite disappointment over the consolidation with the Ames Research Center, Dryden's researchers still found themselves at the edge of exciting new horizons of aeronautical possibility as they moved into the second half of the 1980s and the early 1990s. Advances in computerized control technology were opening the door to new and radical aircraft configurations and integrated systems that would allow aircraft to fly in entirely new regions and conditions. Speed had once been the driver of all fighter designs. Now researchers and designers were looking at configurations that could fly safely at slow speeds and high angles of attack to give an aircraft a tighter turn radius and, therefore, greater maneuverability. The need to learn more about these realms and configurations led to several important research projects in Dryden's fifth decade, including the joint military/NASA X-29 and X-31 programs and the NASA F-18 High Alpha Research Vehicle (HARV).

Further improvements in integrated flight and engine controls also made it possible to consider significant improvements in aircraft safety, including *"smart"* systems that could detect a fault in one control surface or system and compensate with other flight or engine controls. Advances in electronic and fiber optic technology were also creating new opportunities for better and more efficient aircraft systems.

At the same time, high-speed flight research saw a resurgence at NASA with the onset of the High Speed Research (HSR) program in 1990. The program was driven in large part by the idea of developing a High Speed Civil Transport (HSCT), and it led to several high-speed research projects at Dryden in the early 1990s, including work on active supersonic laminar flow, high-altitude radiation effects, and sonic boom propagation. And yet, in another demonstration of Dryden's ability to accommodate and simultaneously pursue a vast and diverse range of research, the early 1990s also saw the beginning of a research program focused on small, remotely piloted, low-speed aircraft designs that could be used for high-altitude environmental research. The Environmental Research Aircraft and Sensor Technology (ERAST) program, as the effort was called, began as a very small side research program at Dryden. But the ERAST program was a first step in exploring a kind of technology and a kind of research and industry partnership that would both become far more influential and commonplace at Dryden in the years to come.

Maneuverability

In addition, the facility continued its support of the nation's space efforts. The explosion of the Space Shuttle Challenger in January 1986 sparked several efforts to explore the safety of various shuttle components and concepts, including research on the vehicles' protective tiles and tires and the addition of a drag chute for landing. At the same time, Dryden was working with industry to explore less expensive ways of accessing space.

Dryden's status within NASA may have shifted, but its work remained as vital, vibrant, and diverse as ever. There were new partnerships to adjust to, but those collaborations were also allowing Dryden, NASA, and industry to explore new and important technological areas – in safety and performance, in systems and configurations, in low-speed and high-speed flight, and in both aeronautics and space.

Dryden personnel in a control room during testing in January 1997. (NASA photo EC97 43959-3)

John A. Manke served as Director of Flight Operations for NASA's Ames Research Center, including the Ames facility at Moffett Field, California, and Dryden Flight Research Facility, Edwards, California. He also served as site manager for Dryden from October 1981 to May 1984. (NASA photo ECN 16340)

Martin A. Knutson became Director of Flight Operations for NASA's Ames Research Center in May 1984 and served in that capacity until December 1990. He also served as site manager of the Ames-Dryden Flight Research Facility, Edwards, California. (NASA photo ECN 29983)

Kenneth J. Szalai became Ames Deputy Director for Dryden on December 3, 1990, and served in that capacity until March 1, 1994, when he became Director of the newly independent Dryden Flight Research Center, which went through a transitional period until September 30, 1994, during which administrative functions separate from those at Ames Research Center were gradually instituted. Szalai remained center director until August 1, 1998. (NASA photo EC98 44622-1)

Significant Research Efforts

Dryden was involved in three significant research efforts from the mid-1980s to the mid-1990s related to exploring and improving aircraft maneuverability. Each program was unique in both focus and organization, however. The first effort was the X-29, which explored an unusual configuration and new technology that showed promise in improving aircraft handling and maneuverability. The second program was the F-18 High Alpha Research Vehicle (HARV), which explored the aerodynamic phenomena associated with the high angle-of-attack flight envelope in which more advanced and maneuverable aircraft would be flying. The third effort was the X-31, a technology demonstrator program sponsored by an international partnership of government, military, and industry. The goal of the X-31 program was to explore and demonstrate the tactical utility of an aircraft capable of vectoring its exhaust for increased maneuverability.

Three center aircraft, left to right, F-104N #811, F-14 #834, and Learjet #221TC flying in formation on June 23, 1987. (NASA photo EC87 0158-11)

The F-18 HARV was a "classic" internal NASA research program in that it was organized and executed as a joint effort between the Langley Research Center and the Dryden Flight Research Facility, with contractor support. In the case of both the X-29 and the X-31, Dryden played more of a supporting role. All three programs were highly successful partnerships that generated significant research results.

From left to right are three thrust-vectoring aircraft flying in formation, Dryden's F/A-18 HARV, the X-31 flown by the International Test Organization from Dryden, and an Air Force F-16 Multi-Axis Thrust Vectoring aircraft that was not associated with Dryden. (NASA photo EC94 42513-03)

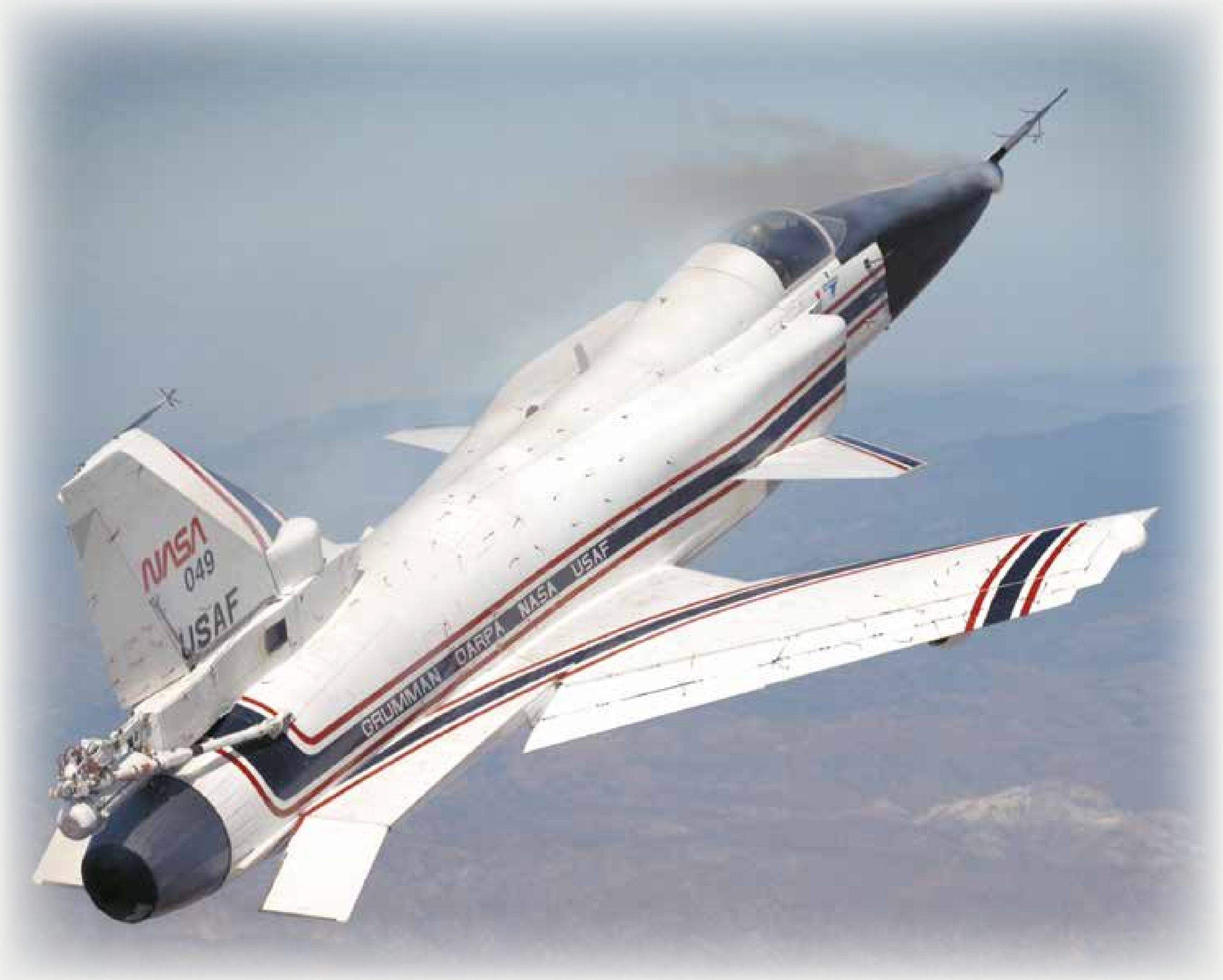
The X-29

The X-29 program resulted indirectly from contractor competition for Dryden's Highly Maneuverable Aircraft Technology (HiMAT) research aircraft. The Grumman Corporation had submitted a proposal for the HiMAT vehicle but the contract was awarded to Rockwell, instead. After losing that contract, Grumman conducted a series of wind tunnel tests at the Langley Research Center to see why its design hadn't fared better in the competition. By coincidence, retired Air Force Colonel Norris J. Krone, Jr. happened to be at Langley during the Grumman tests. Krone, an aeronautical engineer, had written a thesis on forward-swept wing (FSW) configurations, and he suggested to Grumman engineers that the vehicle's performance might be enhanced by making it a forward-swept wing aircraft.

The X-29

Forward-swept wing designs were not a new concept in the late 1970s. Indeed, as early as World War II, the Germans had built and flight tested a forward-swept wing bomber called the Junkers Ju-287. The Hansa HFB 320 business jet built in the 1960s also featured an FSW design. Proponents argued that a forward-swept wing could reduce drag during maneuvering by as much as 20 percent and could also provide better control and performance at high angles of attack (AoA) — a condition researchers refer to as high "alpha."

The problem with an FSW configuration was that at high speeds, aerodynamic forces on the wing would be so great that they could lead to *"structural divergence"*— or, in layman's terms, wings failing and ripping away from the fuselage. With conventional metal construction materials, the only way to prevent that kind of failure is to add significant additional structure. But that additional structure makes the wings extremely heavy, negating any advantage of the FSW design. The advent of improved composite materials such as those successfully demonstrated on the HiMAT research plane, however, gave engineers access to lightweight materials with enough unidirectional stiffness to make an FSW design not only possible, but practical as well.



X-29A #049 is pictured with its fuselage and wings tufted to show airflow patterns during a high angle-of-attack flight on September 13, 1991. The odd structure above the exhaust nozzle is a spin recovery parachute. (NASA photo EC91 0491-07)

With Col. Krone's input, Grumman conducted additional wind tunnel tests on an FSW version of its HiMAT candidate vehicle. The tests showed enough promise that Grumman decided to use company funds to build a full-scale version. Krone, meanwhile, had started working for the Defense Advanced Research Projects Agency (DARPA), where he lobbied successfully for the development of a DARPA-funded FSW technology demonstrator aircraft. Not surprisingly, Grumman subsequently won the contract for what then became the X-29.

The X-29 program was the combined effort of DARPA, the Air Force, NASA, Grumman, and numerous other contractors, and its stated goal was to investigate a number of different advanced aircraft technologies. The primary focus, of course, was the X-29's dramatic FSW configuration. But the composite wing also incorporated a thin supercritical wing section approximately half as thick as the one flown on Dryden's F-8. The aircraft also featured a variable-incidence canard located near the main wing, three-surface pitch control (flaperons on the wing, the canard, and flaps on aft fuselage strakes), and was a highly unstable design.

Aircraft designed to be inherently unstable relied upon computerized flight control systems to provide artificial stability, and the X-29 was not the first such design to be built or flown. Both the F-16 Falcon fighter and the space shuttle, for example, were inherently unstable vehicles. The difference between those designs and that of the X-29 was that the latter was approximately 35 percent unstable while the F-16 and shuttle, by comparison, were only about 10 percent unstable. The percentage of instability refers to the center of pressure location relative to the center of mass of the aircraft: the higher the percentage the greater the instability and degree of risk in flying the aircraft.[1]

An advantage of an unstable aircraft design was that it offered far greater maneuverability. A disadvantage was that a failure of the aircraft's flight control computer would result in the loss of the airplane. The X-29's digital flight control computer made as many as 40 control surface corrections per second to keep the aircraft stable, and researchers calculated that if the computer failed at certain points in the X-29's flight envelope, the aircraft would break up before the pilot could eject. As a result, the X-29's flight control system was designed with three digital computers, each of which had an analog backup. If one computer failed, the other two would "vote" the malfunctioning computer out and take over. If all the digital computers failed, the aircraft would still be flyable using the analog mode.

Single-point Failure

Knowing how critical the X-29's flight control computer was, researchers spent many hours trying to foresee any and all conceivable failure points that might endanger the aircraft. Yet even after the X-29 had been flying for some time, they still discovered several "single-point failure" problems—or places where a single failure would cause the entire system to fail. In one case, a simple light bulb short-circuited during a ground test, sending strange voltages to the X-29's digital flight control computers. It was a minor item, but if it had failed in flight it would have taken out all three digital computers simultaneously, as well as the telemetry system. The aircraft would have reverted to its analog flight control system, but the only person who would have known it was still flying would have been the pilot himself.

Fortunately, the X-29's light bulb problem was discovered on the ground. But the incident underscored how difficult it is to predict every contingency in an advanced-technology aircraft and the new hazards that come with the new capabilities such technology offers. This point was driven home again several years later, with far more serious consequences, when a similarly unforeseen single-point failure resulted in the loss of an X-31 research airplane.

When the X-29 made its maiden flight from Edwards Air Force Base in December 1984, it marked the first time an "X" aircraft had flown at Dryden in more than 10 years. The X-29 program team went on to conduct a total of 429 research flights in two X-29 aircraft over the course of eight years. The first X-29 was used to explore low-altitude, high-speed performance, and the second X-29 investigated the design's performance at low speeds and high angles of attack.

The phase one research results showed, first and foremost, that a highly unstable FSW aircraft could be flown safely and reliably. The X-29 also was able to maintain a higher sustained g load in turns and maneuver with a smaller turn radius than comparable fighters with aft-swept wings. In the second research phase, the X-29 also performed much better than expected at high angles of attack. Pilots found they had good control response up to an angle of attack of about 40 degrees, a marked improvement over conventional fighter designs. Even when the control response began to degrade between 40 and 50 degrees AoA, it did so "gracefully," in the words of one pilot, and one flight even reached a controlled AoA of 67 degrees.

The X-29 with its forward-swept wing design, flies on December 20, 1985. (NASA photo EC85 33297-16)

The second phase of the X-29 research also explored the use of a vortex flow control system to help control the aircraft at extremely high angles of attack. For those experiments, the X-29 was modified with a system that injected air into the vortices coming off its nose. The system wasn't designed to substantially affect the behavior of the X-29, but the technology showed promise for future high-alpha designs.

A forward-swept wing has yet to be incorporated into a production fighter aircraft. But the X-29 research had an immediate impact on aircraft design by adding to engineers' understanding of composites, which are being used more and more extensively in military and civilian aircraft. It also generated valuable information on the use of digital flight control systems, especially in highly unstable aircraft. And the X-29 program unquestionably paved the way for future research into the realm of highly maneuverable, high-alpha flight, both with NASA's F/A-18 High Alpha Research Vehicle (HARV), and with the International Test Organization's X-31 technology demonstrator aircraft.

The F-18 HARV

The second phase of the X-29 research program, NASA's subsequent F-18 HARV research, and the X-31 program were all attempting to explore the flight envelope beyond what researchers dubbed the *"stall barrier"* – the point at which air would no longer flow smoothly enough over an aircraft's wings to generate lift. The tendency of aircraft to *"stall"* and become uncontrollable at high angles of attack and slow speeds was the greatest limiting factor in an airplane's maneuverability, and solving that problem was as difficult as surpassing the infamous sound barrier had been some 40 years earlier.

The F-18 HARV

The X-29 explored one potential design feature that might produce better high-alpha performance. But if aeronautical engineers were going to make substantial progress in designing aircraft capable of operating effectively in that realm, they had to understand it better. The F-18 HARV research program was designed to generate that understanding.

The F-18 HARV program was a combined effort among NASA's Dryden, Langley, Ames, and Lewis research centers. The HARV aircraft was a McDonnell Douglas F/A-18 Hornet fighter, modified with thrust-vectoring paddles on its engine exhaust nozzles to help stabilize the aircraft at extremely high angles of attack. This modification allowed researchers to study and document the aerodynamic forces and phenomena in that region more accurately.

Phase one of the HARV effort began in 1987, before the aircraft was modified with the thrust-vectoring paddles. Researchers used tufts of yarn, dye, and smoke released through ports in the aircraft's nose to study airflow over the vehicle up to 55 degrees AoA. After two and a half years and 101 research flights, three Inconel® thrust-vectoring paddles were installed on the aircraft's exhaust nozzles. The paddles could withstand temperatures of almost 2,000 degrees Fahrenheit and could rotate up to 25 degrees into the engine exhaust to help control the aircraft's pitch and yaw.

With the paddle modification, the HARV reached a controllable AoA of 70 degrees and executed relatively fast rolls at an AoA of up to 65 degrees. The primary mission of the HARV was to validate wind tunnel and computational codes for high-alpha flight conditions. But in addition to providing data to improve design predictions, the F-18 HARV also served as a testbed for numerous high-alpha experiments. At one time, the aircraft was simultaneously conducting 26 different experiments. In addition, although the HARV thrust vectoring was designed primarily as a tool to achieve controllable high-alpha flight, the aircraft began to explore some of the maneuverability and control benefits of thrust vectoring. For one of the later experiments, it was modified with retractable nose strakes that were deployed at high angles of attack to influence the vortices coming off the airplane's nose, significantly improving the aircraft's controllability in those conditions.

The thrust-vectoring technology used in the F-18 HARV is not likely to find application in a production aircraft. Aside from maintenance concerns, the paddle system added 2,100 pounds to the aircraft's weight, most of it at the very back end of the airframe. But the method used with the HARV to reach high-alpha conditions was never the point of the program's research. The goal was to collect data through flights and testbed experiments that would give engineers and designers more information about aerodynamics in the high-alpha realm. The research was also intended to improve the accuracy and reliability of predictive design tools that may one day be used to create more highly maneuverable aircraft. In addition, the F-18 HARV research generated interest in and support for thrust-vectoring technology — a design concept that would receive even more attention through the X-31 research aircraft program.

The F/A-18 High Alpha Research Vehicle (HARV) flies on August 23, 1988, before thrust -vectoring paddles were installed. (NASA photo EC88 0166-06)

The X-31

The X-31 research aircraft was primarily the brainchild of German aerodynamicist Dr. Wolfgang Herbst. Herbst recognized that in the close constraints of an air war in the European theater, good maneuverability would be essential to a fighter's success. If an aircraft could maneuver at high angles of attack, it could turn inside an opponent, giving it a critical combat edge. Herbst also recognized that thrust-vectoring technology could deliver that kind of maneuverability. But Germany did not have the funds to pursue a thrust-vectored research aircraft on its own. So Herbst and a group of German researchers approached colleagues in the U.S. about a joint project to explore the benefits of thrust-vectoring technology. The result was the X-31 program – a highly unusual, international research effort involving DARPA, the U.S. Navy, Deutsche Aerospace (now EADS), the German Federal Ministry of Defense, Rockwell International and, in the last three years of the program, NASA and the U.S. Air Force.

X-31
EFM
164584

The first X-31 (Bu. No. 164584) flies over Edwards Air Force Base, California, in 1993. Aircraft 584 completed 292 flights during the Enhanced Fighter Maneuverability (EFM) program before being lost on January 19, 1995 when icing in the nose probe caused the flight control computer to receive bad data. German test pilot Karl-Heinz Lang ejected after the aircraft became uncontrollable. The program continued, using the second aircraft (Bu. No. 164585). NASA photo EC93-42152-8)

The primary goal of the X-31 program was to research the tactical utility of a thrust-vectored aircraft with advanced flight control systems. Like the X-29, the X-31 was designed with a moveable canard. Unlike the X-29, however, the X-31 had a delta-shaped wing. The composite, twisted-camber wings, the carbon-carbon composite thrust-vectoring paddles and parts of the flight control laws were designed and built in Germany, while the fuselage was built by Rockwell in the U.S. Construction began in the late 1980s, and the first of the two X-31 aircraft flew in February 1990.

The original plan was to have all the initial development work done at Rockwell's Palmdale, California facility. The aircraft was then to be transferred to the Naval Flight Test Center at Patuxent River, Maryland for further flight research. The development and flight testing of the airplane, however, proved far more challenging than anyone anticipated, and delays started to accrue. In a search for additional resources and funding, the X-31 program team asked NASA and the Air Force Flight Test Center at Edwards Air Force Base to become involved.

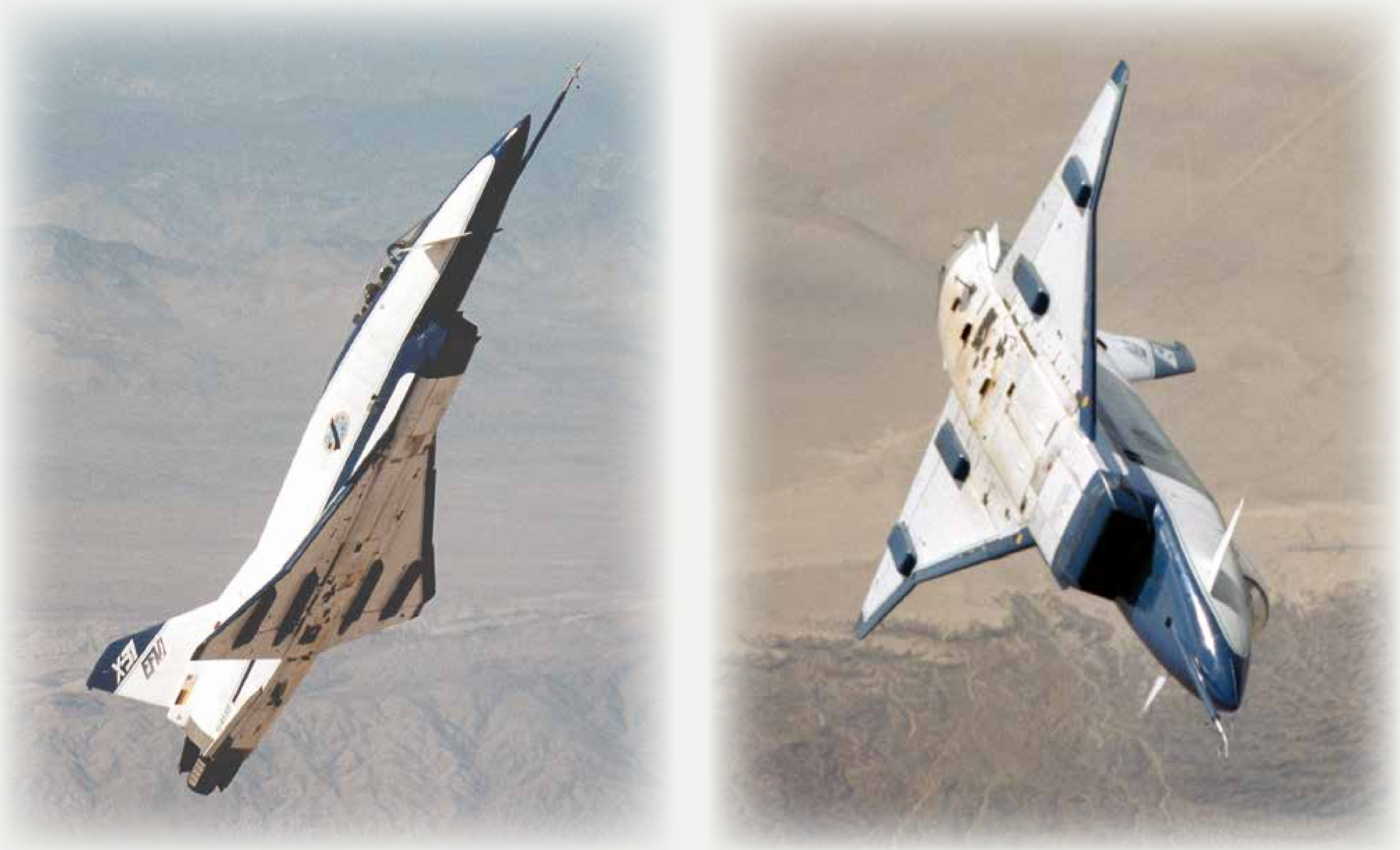
Not everyone at Dryden thought the X-31 was an appropriate research project for the center, because its goal was to investigate practical military applications of thrust-vectoring technology. NASA was a research institution, not a tactical weapons lab. On the other hand, Dryden had a long tradition of working with the military to develop better aircraft, and others at Dryden argued that valuable research information could be gained by participating in the program. And the X-31 program needed the kind of flight test and multi-disciplinary team expertise that had been a hallmark at Dryden for decades. So in 1992, the X-31 research program moved to Dryden.

All partnership efforts can be challenging, but the X-31was a particularly complex program to manage. The biggest difficulty was that it required a diverse team of not just government and industry partners, but government and industry partners from two different countries to work together well. Differences in cultures as well as in approach had to be resolved, and it took some time for team members to develop trust in one another's expertise. "You draw up an organizational chart," one Dryden member of the X-31 team said, "but if you ever have to pull it out of the drawer and actually look at it, you're in trouble."[2]

X-31 Team

Some of the potential turf issues on the X-31 were diffused by consciously downplaying all individual identities in favor of an "X-31 team" identity. Dryden even had special X-31 patches made up for everyone working on the program.

The partnership was also aided by the fact that the new Integrated Test Facility (ITF) at Dryden could house all the team members in the same place. That close proximity encouraged both individual interaction and informal problem solving, which helped the team overcome its significant organizational challenges. In the end, the X-31 team structure, as complex as it was, evolved into one of the most successful research partnerships ever created at Dryden. And because there was only one research goal and agenda for the X-31, there was less tension between the NASA and military team members than had existed in many previous joint efforts.



An X-31 demonstrates a "Herbst maneuver" on March 15, 1994. (NASA photos EC94 42478-04 and EC94 42478-12)

From a technical standpoint, the X-31 aircraft also evolved into a highly successful research vehicle. But that achievement came only after intensive troubleshooting and modification of the original design. The X-31's flight control system went through five major software changes during its years at Dryden, and two additional problems surfaced that were considered significant enough to curtail flight tests until solutions were found.

The first big problem occurred when it became apparent that the pitch control effectiveness of the X-31 in post-stall conditions (particularly at aft-center-of-gravity conditions) was marginal. After the team conducted numerous studies and explored 16 possible fixes in wind tunnel tests at Langley, the decision was made to add rear fuselage strakes to the aircraft to augment its pitch control. Once that was accomplished, the X-31 reached stabilized flight at 70 degrees AoA. But when one of the team's research pilots attempted to reach that mark in a dynamic maneuver, while flying at a higher speed and pulling two or three g's, he got a nasty surprise. The aircraft abruptly departed controlled flight and spun completely around before the pilot managed to regain control.

The X-31 team suspected that asymmetrical nose vortices were the problem, and several researchers suggested that adding nose strakes to the aircraft might provide added lateral stability. The process of exploring, testing, and adding the strakes to the X-31 took a mere seven days, illustrating again the efficient approach and technical agility that flight research engineers at Dryden and other NASA centers relied on to keep flight programs on schedule.

The result of all the structural and software changes, however, was an aircraft that exceeded all performance expectations. In addition to achieving controllable maneuvering flight at angles of attack up to 70 degrees, the X-31 conclusively demonstrated the tactical edge that thrust vectoring could give a fighter aircraft. Researchers had predicted that the X-31 would have a 3:1 kill ratio against contemporary production fighters. But in actual combat maneuvers against an F-18 fighter, the X-31 won approximately 30 dogfight engagements for every one it lost. It also demonstrated maneuvers that no other aircraft could accomplish, including a rapid, 180-degree turn at an extremely high angle of attack while the aircraft almost rotated on its tail, maneuvered by its vectoring system – a maneuver now known as the "Herbst maneuver" in honor of the man who was a driving force behind the X-31.

The Risk of Flight Research

The X-31 logged an X-plane record of 580 flights in 56 months, with 14 pilots from NASA, the U.S. Navy, the U.S. Marine Corps, the U.S. Air Force, the German Air Force, Rockwell International, and Deutsche Aerospace. In later flights, researchers also explored the dynamics of *"quasi-tailless"* flight by modifying the X-31's flight control system to simulate the performance of a tailless aircraft. On those flights, the X-31 relied entirely on its thrust-vectoring system for lateral-directional stability. The results were promising, which could have an impact on future fighter designs, since a tailless configuration would save weight and have a greatly reduced radar cross-section.

For all of its achievements, however, the X-31 program did have one black mark. In a sharp reminder of the risks and difficulties inherent in any flight program exploring new technologies and little-understood regions of flight, one of the two X-31 aircraft was lost in January 1995, on its last scheduled research flight. The accident stemmed from a small, overlooked trouble spot that turned out to be a single-point failure risk. A new pitot tube – called a Kiel probe – that had no heat protection against ice build-up had been installed on the aircraft. Normally, ice wasn't a problem in the arid skies over Edwards Air Force Base. But on that January day, there was a lot of moisture in the air, and the Kiel probe iced over, sending incorrect airspeed information to the aircraft's flight control computers. Thinking the aircraft was traveling slower than it really was, the computers commanded flight control inputs that were too large for the speed the aircraft was actually flying, sending the X-31 out of control. The pilot ejected safely, but the aircraft was lost.

The accident was a shock to the Dryden community, which had gotten accustomed to an excellent safety record. But it illustrated the double-edged sword of advanced technology. The tremendous gains in computer technology made possible much more accurate simulators and computer predictions, so pilots faced fewer unknowns and risks than they had in the center's early days. But as computer technology became more capable, it also made aircraft systems more complex, creating more opportunities for something to go wrong.

The X-31 had been scheduled to fly at the Paris Air Show in June of 1995, which seemed an impossible goal after the accident. But the team decided that it didn't want such a successful program to end on such a low note. So the X-31 team members rolled up their sleeves and dug in. The team completed the X-31 accident report, responded to and incorporated all the report's recommendations, and got the second X-31 back in the air in only 84 days. And less than three months later, the X-31 became the hit of the Paris Air Show, stunning everyone with its impossible-looking maneuvers and performance and proving the worth of not only thrust-vectoring technology, but also the value of taking a concept to actual flight. No one who saw the X-31 fly at Paris that year would ever again question the potential benefits of thrust-vectoring technology. If the events leading up to the X-31 mishap were a reminder of how much vigilance is required to mitigate the risks inherent in a flight test program, the X-31's Paris Air Show performance was a reminder of why those risks are still worth taking.

Integrated Controls (or "Smart" Controls)

Computerized flight and engine controls made concepts like thrust vectoring and the X-31 possible. But integrated controls held the promise of improving more than just the efficiency and maneuverability of an aircraft. If an aircraft could sense problems with individual components and could manage all the other flight and engine controls, it might be able to compensate for damage or malfunctions in an emergency. So during the late 1980s and early 1990s, two separate research efforts at Dryden explored the use of integrated controls to improve both military and civil aircraft safety.

The first project was a Self-Repairing Flight Control System (SRFCS) concept sponsored by the Air Force. Dryden's F-15 research testbed was chosen for the experiments, because it had already been equipped with digital system technology for the HIDEC and Performance Seeking Control (PSC) experiments in the early 1980s. The availability of such a capable testbed made the SRFCS research possible at a reasonable cost.

The SRFCS itself was developed by the McDonnell Aircraft Company and General Electric's Aircraft Control Division. In essence, it used new, integrated flight control software that adjusted the operation of the remaining flight control surfaces to compensate for the damage whenever a malfunction in a component was detected.

Engine Powered Landing

The research flights, which took place in 1989 and 1990, demonstrated that an integrated control system could compensate for loss of individual control surfaces. The aircraft would not have its full maneuvering capabilities, but the SRFCS was also configured to alert the pilot to the problem and the new operating limitations of the airplane. It was an important first step in a new world of *"smart"* aircraft performance and safety.

An even more ambitious research effort in emergency aircraft control was prompted by the 1989 crash of a United Airlines DC-10 in Sioux City, Iowa. Dryden's propulsion branch chief, Bill Burcham, was on a business trip when he read about how Captain Al Haynes and his crew had flown and attempted to land the crippled DC-10 using only the throttles after losing the aircraft's hydraulic system. Burcham was traveling with James Stewart, Dryden's F-15 HIDEC program manager, and the two began talking about whether a computerized propulsion control system could have allowed the DC-10 to land safely. Burcham drew a diagram on a cocktail napkin of how such a system might work, and in five minutes, the two men had outlined a Propulsion Controlled Aircraft (PCA) research effort for the F-15.

Burcham began by attempting to fly an F-15 simulator using only the throttles. By increasing or decreasing thrust, he could make the airplane climb or descend, and by using asymmetric thrust from the two engines, he could make it yaw left and right. It was not a pretty way to fly an airplane, but it seemed that the idea could work. Burcham then enlisted the help of Gordon Fullerton, a former space shuttle commander who had gone to work at Dryden as a research pilot when he left the space program. After a few attempts, Fullerton was able to put the simulator F-15 on the runway every time, so the researchers felt confident trying the concept in flight.

The goal of the initial research flights was to see how well the aircraft could be controlled using only the throttles, without the computerized system. Typically, simulators are more difficult to fly than the actual aircraft, so Fullerton expected the flight to go fairly well. But as researchers at Dryden had been learning for years, flight into new territory did not always go as predicted. As Fullerton recalled from that first throttles-only flight, *"I was looking at the sky, and then the dirt, and all over. I could barely herd [the airplane] through the sky and in the general direction of the airport."*[3]

It turned out that the F-15 simulator performance had assumed identical engines and very smooth response. The engines in the real airplane, however, had slightly different performance and responses. The differences were small, but without the stability augmentation provided by the flight control system they were enough to make the aircraft almost uncontrollable. The good news was that as soon as the computerized throttle control system was implemented, the aircraft became very controllable without the flight control system. It took nine flights to refine the system satisfactorily, but in April 1993 the F-15 made its first complete PCA landing.

The concept not only worked, it clearly made the difference between a controllable and uncontrollable airplane.

Yet the most significant application for the technology wasn't for a fighter, where the pilot had the option of ejecting in an emergency, but in a transport aircraft such as the United DC-10. So after the F-15 flights, Burcham worked out an agreement with McDonnell Douglas to conduct some PCA experiments on an MD-11 airliner. The MD-11 successfully demonstrated the first throttles-only landing of a transport aircraft in August 1995, using the PCA system. After a few more months of work, Dryden researchers got the PCA system to work with the airliner's autoland system, so a crippled airliner could land safely without the pilot having to manually fly the PCA system.

A McDonnell Douglas MD-11 attempts the first-ever controlled landing of a transport aircraft using only engine power for the landing. Flown by former astronaut Gordon Fullerton, the aircraft used a Propulsion-Controlled-Aircraft (PCA) system involving standard autopilot controls in conjunction with new programming in the airplane's flight-control computers to enable a landing when normal control surfaces were not functional. (NASA photo EC95-43247-1)

Clearly, the technology worked and offered airliners a vastly improved chance of survival following the kind of catastrophic hydraulic failure that Captain Haynes' DC-10 had experienced. But in a telling illustration of why transferring new technology to industry is often a complicated process, the PCA system was not adopted by the airlines or airline manufacturers. Against the potential safety gain offered by the PCA software, airline manufacturers and their customers had to balance the fact that changing the software on their engines would nullify the warranties on the equipment for an extra safety margin in a situation that was very unlikely to occur.

In an effort to respond to industry's concerns and limitations, Dryden propulsion researchers developed what they called *"PCA Lite,"* which did not require changes to the engine software. Instead, PCA Lite used the five percent engine pressure ratio (EPR) trim allowance and the aircraft's autothrottle system to generate a less effective but still workable level of pitch and roll control in the event of a flight control or hydraulic failure.

The PCA system was not immediately incorporated into any production airliners. However, the story of Dryden's PCA research also clearly illustrates the value of maintaining a strong and forward-looking national aeronautical research capacity, even if there is no clear and immediate need for some of the technology being developed. For in 1995, 1998, and 1999, when the PCA research flights and PCA Lite simulation studies were conducted, the remote chance of a catastrophic hydraulic failure wasn't a high enough risk to compel industry to incorporate the new technology. But then the terrorist attacks of September 11, 2001, occurred, and the world changed. Suddenly, airliners and the new Department of Homeland Security were contemplating terrorist attacks and potential missile strikes that could take out an airliner's control surfaces or hydraulic system. So interest in the PCA concept reemerged, because it was then viewed as a potentially important defensive measure against a threat that didn't exist when the technology was developed.

F-18 SRA

Many of Dryden's aircraft have served not only as a primary test vehicle for a particular research program, but also as test platforms for *"piggy-back"* or additional small research experiments. But as technology development began to center more on internal aircraft systems, testbed aircraft with flexible system architectures became a far more valuable research asset. The highly capable F-15 testbed that conducted the HIDEC, SRFCS, and PCA work was one example, but it was not the only aircraft at Dryden in the late 1980s and 1990s capable of conducting systems research. In the 1980s, engineers at Dryden suggested including some small system research experiments on one of the center's F/A-18 chase planes. Since the F/A-18 would be flying regular support missions anyway, it offered a chance to conduct some small-scale systems research at low cost – something Dryden engineers were always looking to do.

One of NASA's F/A-18 Hornets on the ramp at the Dryden Flight Research Center, Edwards, California at dawn August 6, 1993. F-18 aircraft, on loan to NASA by the U.S. Navy, were flown at Dryden as support aircraft and as research testbeds. As support aircraft, they were used primarily for safety chase, pilot proficiency and aerial photography. As research aircraft, they were involved in thrust vectoring and high angle of attack research, as well as numerous smaller scale experiments. (NASA photo EC93-42116-2)

Systems Research Aircraft

Once industry researchers became aware that Dryden had a cost-effective testbed for advanced systems technology, the number of research experiments on the F-18 grew, and the aircraft became a full-time flying test platform. By the end of 1995, Dryden's F-18 Systems Research Aircraft (SRA) had 12 separate experiments flying on it, with another 11 planned, and it had flown experiments in support of most of the major electronic manufacturers in the country.

The initial research with the SRA focused on *"distributed"* aircraft system technology designed to replace many centralized systems with smaller, self-contained components. Decentralized systems have numerous advantages, including less susceptibility to electromagnetic interference (EMI) and battle damage, and reduced maintenance costs. The technology also enabled designers to use active flutter-suppression techniques, which could make aircraft more efficient by reducing the need for heavy aircraft structure.

The SRA was also used to research fly-by-light technology that used fiber optic sensors to operate selected control surfaces, flush-mounted air data systems, and new composite-structure actuators. The F-18 SRA was such a testbed for this kind of research, because it had two of most components, including engines and vertical stabilizers. Consequently, engineers could modify one control surface or engine with experimental sensors or components and still have another that was conventionally configured, increasing the safety margin of the research.

Many of the technologies explored on the SRA were concepts that, like digital fly-by-wire, were still too immature or high-risk for industry to incorporate into production aircraft. But the F-18 SRA offered the opportunity to develop the concepts and generate confidence in the technology both safely and cost effectively, allowing manufacturers to explore more advanced systems that they would not have had the resources or ability to develop on their own.

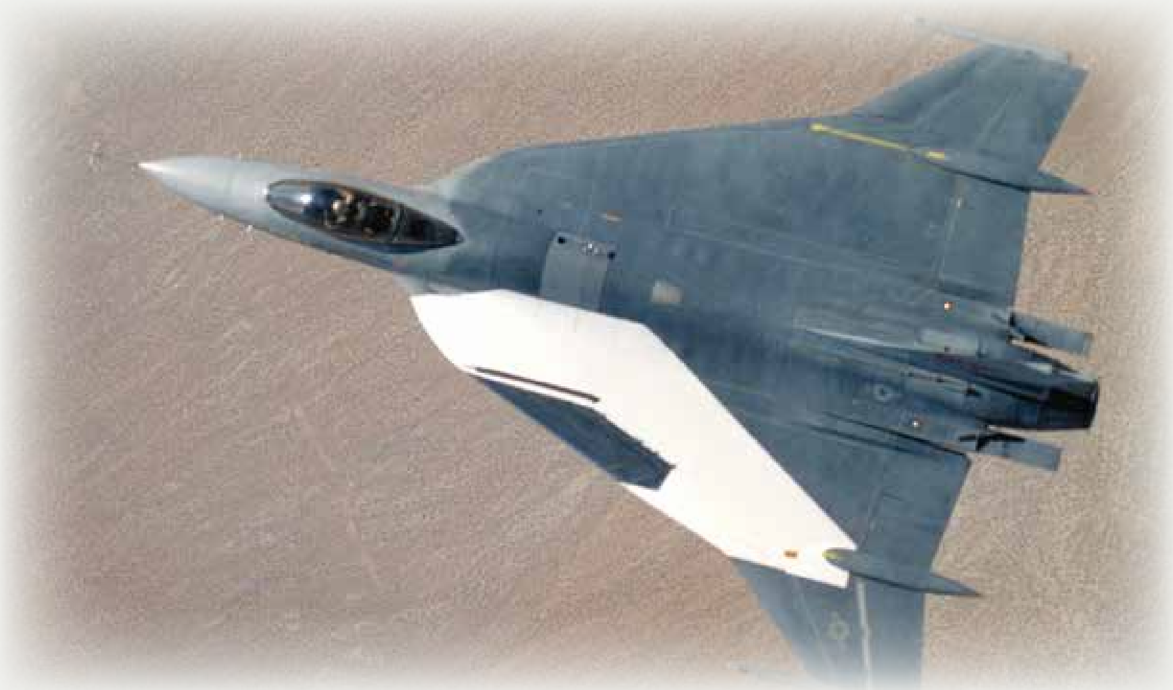
High-Speed Research

Advances in computerized control technology and aircraft systems may have dominated much of Dryden's research work in the late 1980s and early 1990s but, in the continually rising and falling tides of national priorities, high-speed flight research also saw a resurgence as the 1980s came to a close. NASA and industry joined together to pursue a concept known as the High Speed Civil Transport (HSCT) – a supersonic passenger jet whose goal would be to carry 300 passengers at more than twice the speed of sound, but far more cost-effectively and efficiently, and with less of an environmental impact, than the Concorde SST. Within NASA, the HSCT became part of a High Speed Research (HSR) program that sparked new research projects at Dryden as well as other NASA centers.

Supersonic Active Laminar Flow

One of the early high-speed research efforts was a follow-on project to the earlier active laminar flow experiments Dryden had conducted with the JetStar aircraft. The hardware and systems necessary to create active laminar flow might not be practical for subsonic aircraft, but on a Mach 2+ aircraft like the HSCT, a nine percent reduction in drag that a laminar flow wing might generate could translate into a significant increase in payload or range.

Rockwell International had begun its own research on active laminar flow and, in 1988, Dryden acquired two cranked-arrow wing F-16XL prototypes that the Air Force was preparing to scrap but agreed to loan to Dryden instead. Rockwell approached Dryden and suggested a joint supersonic laminar flow control research effort, using the F-16XL aircraft and a test section "glove," or wing covering, manufactured by Rockwell. A first set of research flights began in 1991, using a small, perforated titanium wing glove and a turbo compressor for the laminar flow control. The implementation was a little crude, but the results were promising enough to prompt a follow-on research effort with the second F-16XL.



F-16XL #1 with a test-section "glove" (white area) is in flight after supersonic laminar-flow research had begun on August 23, 1991. (NASA photo EC91 0458-05)

Mission Adaptive Wing

Like Rockwell, Dryden also had been pursuing laminar flow research long before the HSCT came along. But the official laminar flow control program illustrated again how even ongoing research efforts can be affected by changes in national priorities. When NASA, Congress, and industry decided to pursue a formal HSCT program, the smaller-scale laminar flow research at Dryden was suddenly pulled into a high-profile focused program that generated more funding and support for that work.v

The HSCT program also created the need for new partnerships at Dryden. Because of the new link between the laminar flow research and a tangible HSCT aircraft, Dryden's researchers found themselves working directly with the transport aircraft manufacturing industry, which became an educational experience for everyone involved. The engineers at Boeing and McDonnell Douglas were not accustomed to some of the considerations involved in high-performance flight research, such as the fact that an F-16XL flying at supersonic speeds could not execute turns without considering the airspace available and the sonic boom footprint. By the same token, research engineers at Dryden did not have experience with some of the constraints of the transport industry, such as the need to maneuver in a manner that would always provide a smooth, comfortable ride for passengers.

Consequently, the F-16XL partnership generated more than just knowledge about a potentially beneficial new technology. It also allowed Dryden's research engineers to gain valuable insight into the needs and technology constraints of an industry that will ultimately apply some of the technology Dryden is working to develop.

Mission Adaptive Wing

At the same time as Dryden was investigating supersonic laminar flow for the transport industry, it was also continuing research on improving wing designs for supersonic military aircraft. In the second half of the 1980s, Dryden explored a next-generation approach to wing design, using the center's F-111 Transonic Aircraft Technology (TACT) vehicle. The research was part of a program called Advanced Fighter Technology Integration (AFTI), and the initial AFTI experiment was called the Mission Adaptive Wing (MAW). The MAW started with a supercritical wing, but it then went one step further by incorporating internal controls that flexed the wing to adjust the amount of its camber (curvature) to adapt to different flight conditions.

The Advanced Fighter Technology Integration (AFTI) F-111 with a Mission Adaptive Wing (MAW), is in flight on May 8,1986. (NASA photo EC86 33439-02)

The MAW could flex enough to generate the additional lift needed for slow speeds, eliminating the need for lift-producing devices such as slats and flaps; change to a supercritical wing airfoil for transonic flight; and then adjust to a near-symmetrical wing section for supersonic speeds. The F-111 AFTI flight research lasted from 1985 to 1988, and it indicated that the drag reduction from a MAW design could increase performance from 8 to 20 percent in different flight conditions. The information gained from the AFTI research came too late to be incorporated into the Advanced Tactical Fighter (ATF), but it may well be used in future fighter aircraft. It also paved the way for further research into even more capable, flexible, and adaptable wing designs.

Space Support

In addition to its role as a primary, and then secondary, space shuttle landing site, Dryden also conducted numerous research experiments in support of the shuttle program after the shuttle began regular space flights. In one effort, Dryden conducted a series of flight tests on the tiles being used for the orbiter's thermal protection system. Because the shuttle was launched from Florida, where rain is common, managers at the Johnson Space Center wanted to determine what kind of damage rain would inflict on the critical thermal tiles.

Dryden researchers installed some of the rigid thermal tiles on a special flight test fixture underneath one of the center's F-104 aircraft and measured the results from flight in both actual rain and behind a KC-135 spray tanker. The flights provided valuable data. Not surprisingly, tiles that had been through several launch cycles appeared to fail at lower impact forces than new tiles. But the research also indicated that the shuttle could be launched or landed in light rain, although there were numerous variables that needed additional investigation. Related research also indicated that the flexible protective tiles could actually withstand launch airloads as much as 40 percent higher than they were designed to bear.

Following the Challenger accident in January 1986, NASA also began looking at other potential weak spots in the orbiter, main fuel tank, and booster rockets that could cause problems for future missions. One possible trouble spot was the orbiter's landing gear and tires. Because it was so difficult to protect the tires and gear in the extreme temperatures and environments experienced by the shuttle, the orbiters were equipped with only four small wheels, two on each main gear. The main gear systems of a similar-weight commercial airliner, by comparison, incorporated anywhere from 8 to 16 wheels.

Although the shuttle tires had been tested at the Langley Research Center test track and on a stationary device called a dynamometer, the *"dyno"* could not test all the forces the tires had to endure in actual flight. Engineers from the Johnson Space Center and Dryden agreed that it would be helpful to explore the actual limits and failure modes of the shuttle tires and wheels in real-life conditions, if a suitable test aircraft could be found.

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F-104G #826 flies on December 8, 1993. This Lockheed aircraft had flown at the center since June 1975. Among other missions, the F-104G flew research flights with the space shuttle thermal tiles before its retirement in 1994 after 1,415 total flights at Dryden. (NASA photo EC93 42325-22)

Space Shuttle Atlantis lands at Edwards Air Force Base in the early dawn of March 30, 1996. (NASA photo EC96 43494-3)

Convair 990 Tire Test

As it turned out, NASA already had a transport aircraft that could achieve both the gross weight and speeds of the shuttle. The airplane was a Convair 990 – a plane whose heavy, overbuilt design helped prevent it from being a commercial success but made it perfect for flight research. The Convair was pulled out of storage and modified with a separate test gear mechanism between the aircraft's existing main landing gear. The test mechanism used landing gear components from the shuttle and was powered by a high-pressure hydraulic system that allowed it to be extended and tested at various loads after the Convair touched down on its own gear. This setup also provided an important margin of safety for testing tire failures, since the test apparatus was supplemental to the Convair's existing gear.

Although the initial goal of the research was to test failure modes, NASA eventually decided that testing tire wear and stress on landing was a more important priority. Ground analysis had led program managers to limit the shuttle to landing with less than a 12- to 15-knot crosswind, which also limited launches, because in order for a launch to be approved, conditions had to be good enough for the shuttle to perform an emergency return-to-launch-site (RTLS) maneuver. If data from flight tests indicated that the tires could withstand greater side forces, the crosswind limits could be increased.

Dryden's research with the modified Convair 990 began in 1993, and included two trips to Florida to test the tires at the speeds and weight the shuttle would land if it had to perform an emergency RTLS maneuver. The results were surprising, and not encouraging. The tests indicated that the tires might not even sustain crosswinds as high as the predicted 12- to 15-knot limit. The Kennedy Space Center had grooves cut into the concrete to improve traction in wet weather, but the grooves created extra friction wear on tires – especially the small, heavily loaded tires of the shuttle. As a result of the Convair tests, NASA decided to smooth the runway surface somewhat, raising the shuttle's crosswind capacity from 15 to 20 knots.

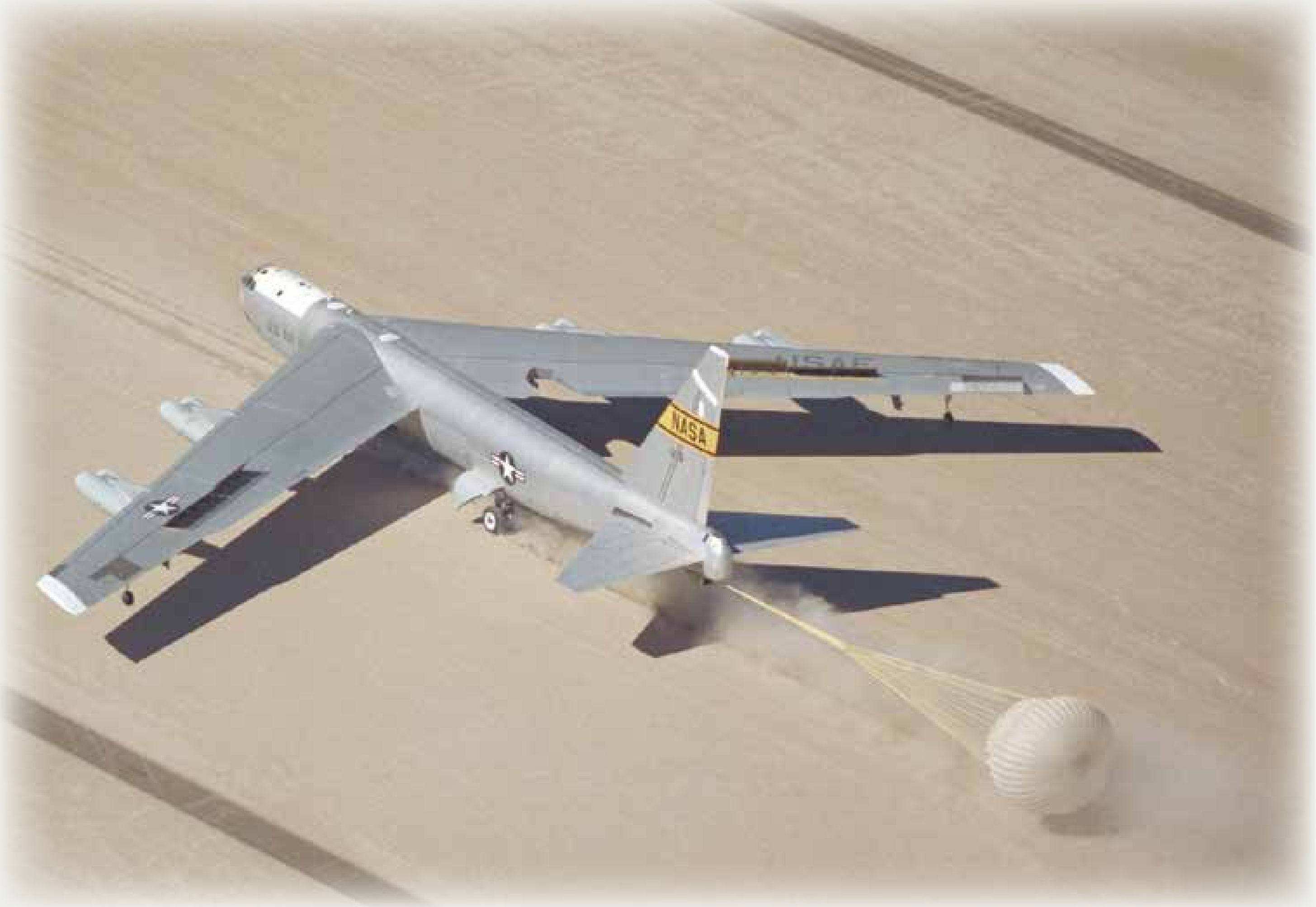
The Convair 990 lands during the final space shuttle tire test on August 12, 1995. (NASA photo EC95 43230-4)

The Space Shuttle Drag Chute

At the same time, research with the Convair explored the performance and limits of the tires in both high-speed-landing and low-tire-pressure conditions. The results showed that the tires could withstand these conditions better than engineers had thought. At the time of the tests, shuttle procedures called for an immediate return to Earth if the pressure in the tires (which is monitored the entire time the shuttle is in space) fell below 310 psi. But after the Convair test gear showed that the tires could still operate safely down to 200 psi, the required minimum pressure was reduced to 270 psi, giving the shuttle extra operating margin, and potentially preventing an unnecessary emergency return flight.

Near the end of the shuttle tire experiments, researchers finally got back to their initial area of interest – the failure modes of the tires and wheels. In two August 1995 flights, a test tire was intentionally failed and kept rolling under load, first on the paved Edwards runway and then on the Rogers lakebed. The results on the runway were dramatic. As the wheel was ground down by the concrete surface, the fire ignited by the heat stretched as high as the passenger windows and beyond the tail. The same test on the lakebed produced very different results. The tire and wheel kept rolling, and there was no fire – information that certainly helped managers evaluate the best course of action if the shuttle ever had to land with a defective tire.

Dryden's NB-52B launch plane was enlisted to flight test a drag chute for the shuttle in 1990. The orbiter was already landing on concrete runway surfaces both at Edwards and at the Kennedy Space Center, but a drag chute could give the shuttle pilots an extra safety margin, as well as reduce the wear on the shuttle braking system. Dryden's NB-52B was recruited as the research aircraft because it was already equipped for a drag chute, and it was heavy enough to produce a load on the chute similar to that of the orbiter. A series of landing tests on both Rogers Dry Lake and the Edwards runway showed that the drag chute worked well, and the chute was installed and used for the first time on the new orbiter Endeavor in 1992. The other orbiters were subsequently retrofitted with the same drag chute system, enhancing the safety of all future shuttle landings.



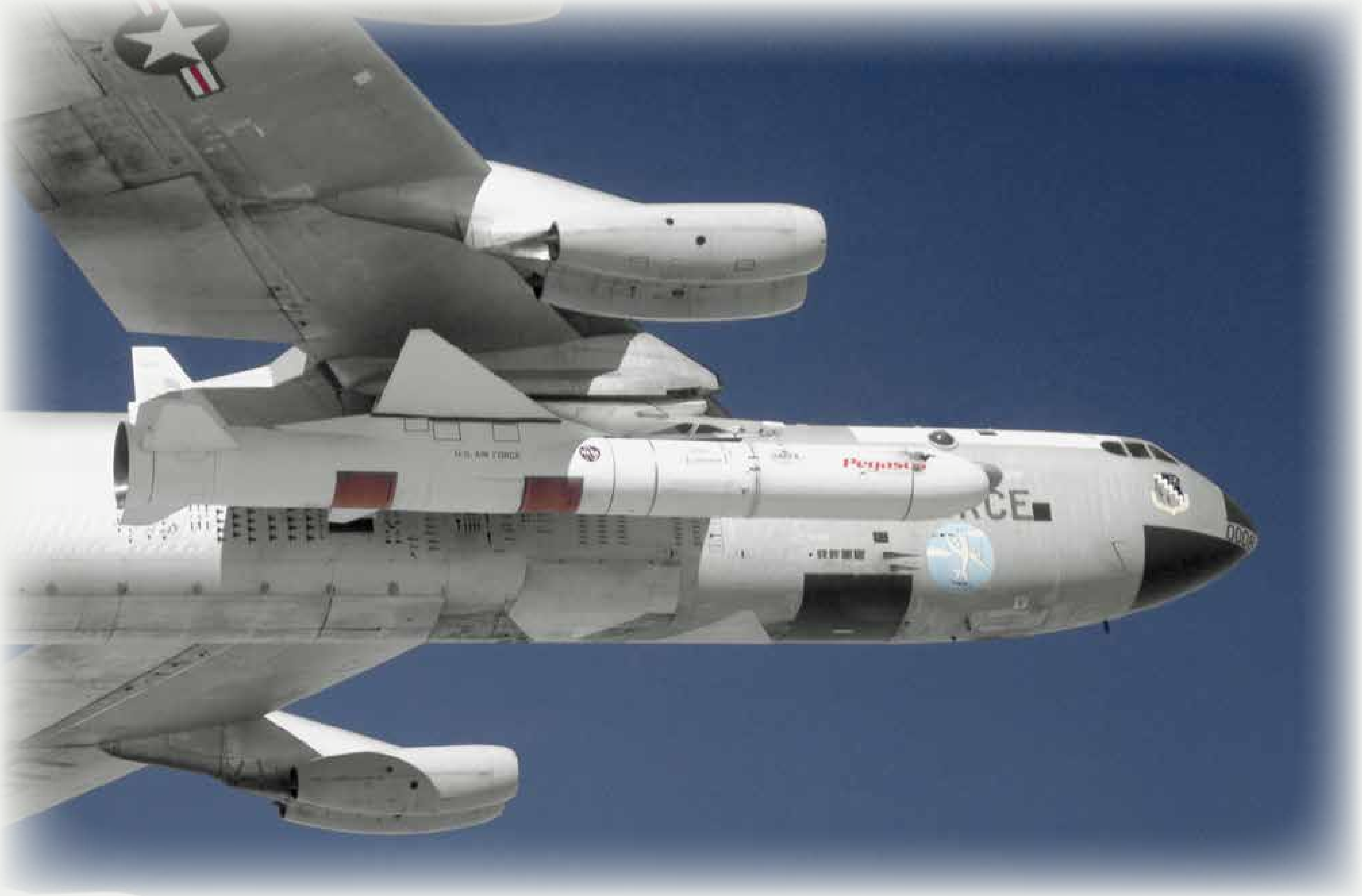
Dryden's venerable NB-52B testing a drag chute designed to add to the space shuttle's safety margin as well as reduce tire wear, August 30, 1990. (NASA photo EC90 0257-21)

United States

The Space Shuttle Discovery lands at Edwards Air Force Base on October 24, 2000, using the shuttle drag chute tested by Dryden from 1990 to 1991 to make shuttle landings safer and easier. (NASA photo EC00 0311-03)

Pegasus

Dryden's NB-52B was also used for another small but significant space-related research effort in the early 1990s. In the late 1980s, a group of industry entrepreneurs approached Dryden about using the center's NB-52B to help them test a new and potentially more cost-effective way of getting small payloads into orbit. Under the sponsorship of the Advanced Research Projects Agency (ARPA, now the Defense Advanced Research Projects Agency, or DARPA), the Orbital Sciences Corporation had developed an air-launched rocket booster system in which the launch aircraft would replace the first stage of what would otherwise have been a four-stage launch system. In Orbital's system, the launch aircraft released a winged booster rocket, which carried a second booster rocket and payload even higher. The final rocket stage lifted the 1,500-pound payload into orbit.



Dryden's NB-52B carries a Pegasus® launch vehicle on its first captive flight, November 9, 1989, in preparation for the first launch of the Pegasus® from beneath the NB-52B in April 1990. (NASA photo EC89 0309-03)

Orbital Sciences named the winged launch rocket *"Pegasus®"* and teamed with the Hercules Corporation for manufacture of the rocket motors, and Scaled Composites for the booster system's wing. But the vehicle still needed a suitable launch aircraft, and the custom launch pylon on Dryden's NB-52B made it a logical choice – as well as a valuable asset for the fledgling commercial space launch industry.

Dryden's research pilots carried the first Pegasus® aloft under the NB-52B's wing in April 1990. The launch was successful, and it marked one of the first times a commercial company had launched a payload into Earth orbit. Five additional launches between 1990 and 1994 were also successful, opening a door not only to potentially less expensive methods for reaching orbit, but also non-governmental space access and commerce.

ERAST

At the same time Dryden was pursuing research into space, high-performance configurations, and complex aircraft systems, it also was starting a low-key effort into an unassuming, low-powered area of flight that would, nonetheless, evolve into one of the most significant new frontiers in aeronautics – low-speed, high-altitude, long-endurance flight by uninhabited, or remotely piloted, aircraft.

In the 1980s, several entities were exploring possible technology and aircraft configurations to achieve high-altitude, low-speed flight. The Ballistic Missile Defense Organization (BMDO) funded two classified programs to develop potential designs for the Theater Operations (Raptor) program – AeroVironment's Pathfinder and Scaled Composites' Raptor (known in the ERAST program as the Demonstrator 2). Another configuration, the Aurora Flight Sciences' Perseus, was developed under the auspices of the High Speed Civil Transport program, because a low-powered, high-altitude endurance aircraft could be useful in mapping emissions and sonic boom propagation created by a high-speed, high-altitude transport. Ames Research Center was also helping to develop a low-powered, high-altitude vehicle to support its airborne environmental research. Ames had a DC-8 and two ER-2 aircraft for conducting atmospheric research at high altitudes, but they were expensive to operate and limited in the type and duration of research they could conduct.

ERAST Program

By the early 1990s, however, all of those research efforts concluded that the technology just wasn't mature enough to make an uninhabited, high-altitude, long-endurance aircraft successful. Dryden had been assisting the BMDO on some low-altitude test flights of its prototype vehicle, and the center was already involved in NASA's HSCT program. So NASA Headquarters and Dryden managers began to explore what might be done with these early prototype vehicles as their initial development funds tapered off. Eventually, the idea emerged of putting together a program that could help support not only the development of the high-altitude unmanned aerial vehicle (UAV) aircraft and sensor technology, but also the development of a robust UAV industry that could incorporate that technology into production aircraft.

The resulting research effort was called the Environmental Research Aircraft and Sensor Technology (ERAST) program, and it was groundbreaking on several levels. For one thing, the realm the program was developing technology to explore – slow, high-altitude flight – had never been conquered before. To develop a remotely piloted vehicle capable of sustaining flight for long periods of time at altitudes above 50,000 feet required new, lightweight structures, innovative engine technology, and miniaturization of numerous systems. But to concurrently nurture the development of a robust, private UAV industry required a different kind of program management structure than Dryden, even with its wide variety of partnership arrangements, had ever created.

With most research efforts conducted at Dryden, the center retained a fair amount of control. But the ERAST program was set up under a new arrangement called a Joint Sponsored Research Agreement (JSRA), which left far more control in the hands of an industry consortium that worked together, with NASA's support, to develop basic technology in a particular field. The research results were to be shared among the consortium members, who could then incorporate that information and technology into proprietary products. With a JSRA, NASA provided funding, coordination, and program support but it did not call the research shots.

The appeal of the JSRA for the four companies who decided to participate was that, at the time the ERAST JSRA was developed, there was no strong commercial market for UAVs, so research and development funding was hard to come by. NASA offered that funding, in return for the participants' willingness to contribute to a joint effort and share the research results among all members.

If that was a bit of a difficult pill for the industry members to swallow initially, the surrender of control was equally difficult for Dryden to accommodate. Unlike other research efforts, the ERAST program allowed the participating companies to be responsible for their own flight safety. Their vehicles did not go through Dryden's stringent Flight Readiness Review committee procedures – a change NASA and Dryden allowed only because there were no pilots onboard the aircraft. Even so, the new guidelines were a significant enough departure from NASA's standard procedures that Wesley Harris, NASA's associate administrator for aeronautics, felt the need to address this exception in a special memo to the associate administrator for safety and mission assurance. In essence, the memo acknowledged and accepted the probable loss of some ERAST program vehicles, as long as ground safety was assured.[4] Dryden retained responsibility for range safety, which meant ensuring that each design included an acceptable flight termination system to bring the aircraft down in a predictable area in the case of a mishap.

The program was not initially popular at Dryden. The center wasn't in control of the research, and the ERAST vehicles were slow, low-powered, unmanned aircraft – a far cry from the intoxicating thunder of the *"big iron"* aircraft that had long been the lifeblood of the center. And yet, the staff who worked on the ERAST program soon became passionate advocates of the potential this new technology offered, and the new realms the little aircraft were starting to explore. A passion for exploration, after all, is the reason most of Dryden's researchers came to work at the remote desert center, and that motivation endured even when that exploration happened at 25-30 mph, with the pilot on the ground.

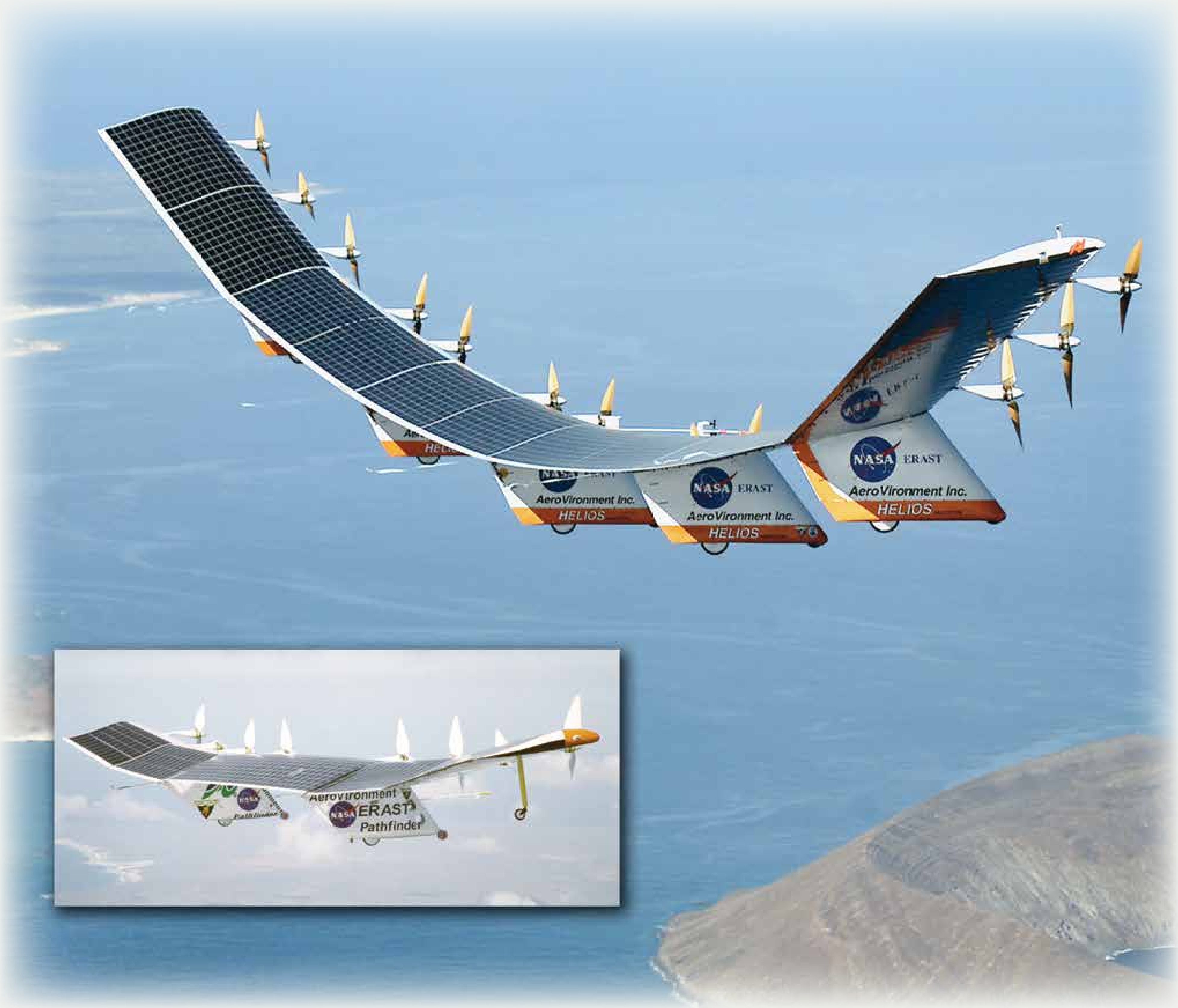
The ERAST program officially began in 1994. The partnership included NASA's Dryden, Ames, Langley, and Lewis (now Glenn) centers, the FAA, the Department of Defense, the Department of Energy, and four main industry members: General Atomics, AeroVironment, Scaled Composites, and Aurora Flight Sciences Corporation.

ERAST Program

Several flights of the ERAST program were airborne by 1995. The Perseus A, built by Aurora, was designed for sustained flight at 80,000 feet. It was built with an experimental gasoline/liquid-oxygen engine, because one of the challenges in achieving lightweight, high-altitude flight stems from the fact that the air is too thin to support normally aspirated gasoline engines. The Perseus A reached 50,000 feet on one flight, but subsequent testing revealed that the engine needed further development. Unfortunately, as the Harris memo anticipated, the Perseus A was lost on a flight in November 1994 after an autopilot gyro malfunctioned on its 16th development flight. However, Aurora had already begun flight tests with a follow-on design called the Perseus B, which utilized a more conventional engine. There were other UAV crashes as well, and collectively the crashes showed the technology wasn't mature. But bringing the UAV technology to maturity was precisely one of NASA's goals, and these events were to be endured along the way.

The second ERAST aircraft that flew in the first half of the 1990s was AeroVironment's solar-powered Pathfinder. AeroVironment's founder, Paul MacCready, had already achieved worldwide acclaim with his human-powered Gossamer Condor aircraft, and the company specialized in extremely lightweight wing designs. The Pathfinder was an extremely lightweight flying wing that had the wingspan of a Boeing 737 but weighed only 530 pounds, giving it a wing loading of only 0.6 pounds per square foot. Its engine power was provided by six solar-powered electric motors that were designed to reach an altitude of 65,000 feet. In September 1995, the Pathfinder set a national electric-powered aircraft altitude record of 50,567 feet.

Over the next 10 years, the ERAST program flight-tested nine different aircraft designs. When the program started, the technology had a long way to go and the market for UAVs was questionable. Solar wings and other ERAST UAV aircraft continued to demonstrate their utility in NASA science missions that observed crops, monitored shoreline, and tested communications. In addition, the Helios Prototype achieved one of the ERAST goals by reaching an altitude of 96,863 feet on 13 August 2001. By the time the program ended, UAVs had evolved into a highly competitive option for not only environmental research, but reconnaissance, surveillance, search and rescue, aircraft component research, and high-risk military missions.



Another AeroVironment solar-powered aircraft in the ERAST program, the Helios prototype flew over the Hawaiian Islands on July 14, 2001. (NASA photo ED01 0209-05)

(Inset)Aero-Vironment's Pathfinder Plus aircraft flew on June 17, 1998. This was another solar-powered aircraft, a follow on to the original Pathfinder in the ERAST program. (NASA photo EC98 44621-252)

Conclusion

Even as Dryden lost its status as an independent NASA research center, its work was expanding into exciting new areas. The focus of Dryden's research remained an eclectic mix of speed, high-altitude flight, efficiency, safety, systems, and new configurations, and it continued to support both space and atmospheric flight. But technology breakthroughs in computerized and integrated controls, materials, remotely piloted vehicles, and space launch systems were opening doors to completely new configurations, realms, and types of flight.

There were serious challenges involved in these new horizons, of course. The technology was complex, which meant that there were many more opportunities for problems to occur. A small item like a frozen pitot tube could now cause the loss of an aircraft. But the partnerships required to pursue goals like an international X-31 research plane or the development of a robust UAV industry were now far more complex as well. The good news was that people who worked at Dryden tended to stay there for a long time. So the lessons they learned not only in how to conduct successful flight research, but also in how to work with a variety of partners in constantly evolving partnership arrangements could be stored in memory and applied to the next project that appeared over the horizon.

As Dryden approached its half-century mark, many of the old, established structures were changing. The old boundaries of national interest were blurring into a new era of international cooperation. The days of the X-15 rocket ships were giving way to a world where computer systems and solar-powered technology played a far more important role; where the rocket men sometimes found themselves flying aircraft from remote ground stations. As industry matured, the role of NASA and Dryden in supporting new efforts needed to change, as well, leading to a wider variety of partnership arrangements. The JSRA that governed the ERAST program was perhaps an extreme example of that shift, but to remain relevant and helpful to industry, Dryden had to develop even more flexibility in the role it was willing to play.

The good news was that the research Dryden conducted in its fifth decade proved once again that the center was capable of making those adjustments and was still a relevant and important resource for both the aerospace industry and the nation as a whole. The center's achievements between the mid-1980s and the mid-1990s ranged from significant advances in efficiency, maneuverability, and thrust-vectoring technology to improved safety for future airliners, to a whole new class of aircraft that could explore and help protect the Earth's atmosphere, to safer shuttle operations and lower-cost access to space.

There was also one more achievement that, at least as far as Dryden's employees were concerned, was an important mark of its contributions to NASA, industry, and the nation. After concerted lobbying by Dryden managers for a number of years, NASA headquarters finally decided that the consolidation of Dryden with Ames had caused more administrative problems and delays than it had solved. So in March 1994, Dryden's status as a full-fledged, independent NASA research center was reinstated.

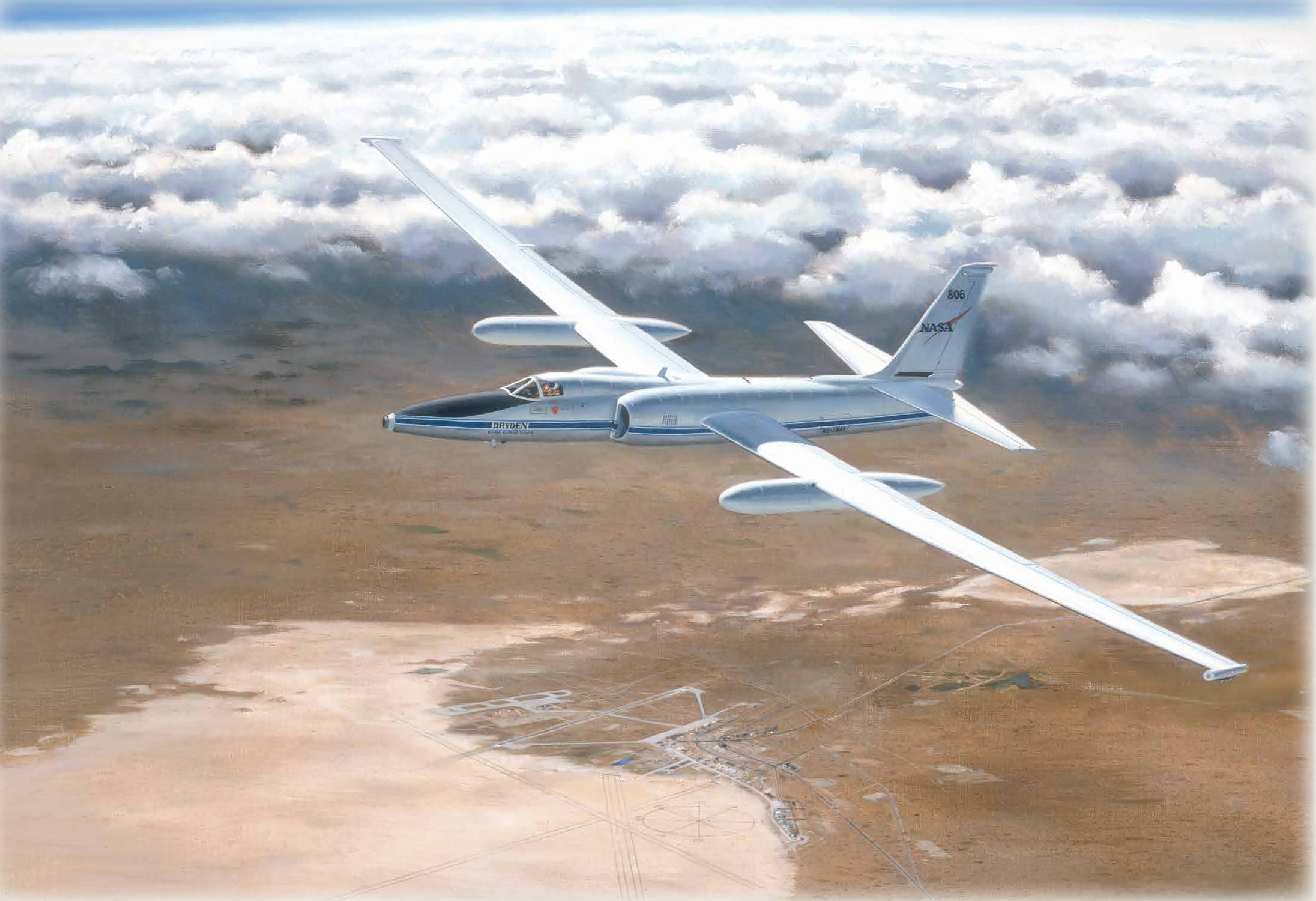
Research priorities would continue to change, partnerships would evolve, and specific projects would come and go. But fifty years after its founding, Dryden was still helping to make making important breakthroughs in aerospace technology and capability and opening up new horizons and worlds of flight.

1 Hallion and Gorn, On the Frontier, p. 280.

2 Rogers Smith, interview with author, Edwards, California, 19 July 1995

3 Gordon Fullerton, interview with author, Edwards, California, 7 September 1995

4 Wesley L. Harris to Frederick D. Gregory, memo, 17 June 1994, from John DelFrate personal files, Dryden Flight Research Center, Edwards, v.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NASA
DRYDEN

Chapter 7

Accessing Space, Understanding Earth

ER-2 Altitude Record: 1998 Collier
Trophy Winner
by Nixon Galloway

A U.S. Navy E-2C Hawkeye in Dryden's Flight Loads Laboratory (FLL) undergoing load analysis. The FLL offers load and heat stress analysis for NASA and other customers. (NASA photo EC04 0360-75)

Space Exploration

As Dryden began its second half-century of operation, the frontiers of technology and the tides of national priorities and international politics had shifted yet again. The Cold War had ended, changing some of the military's requirements for aircraft and technology. Environmental research and concerns had become a higher national priority, while support for a high-speed civil transport had waned once again. There was a growing urgency to replace the aging space shuttle while still supporting the International Space Station. NASA had also been tasked with finding less-expensive ways to reach space, spawning research into projects ranging from small, less-expensive launch vehicles to new rocket engine designs and hypersonic, scramjet propulsion systems and vehicles.

At the same time, advances in technology were opening up exciting new horizons and possibilities in aeronautics that begged further exploration and experimentation. Computing power and avionics had advanced enough that unmanned vehicles were beginning to evolve into practical aircraft designs. Research on integrated engine and flight control technology was reducing the gap between experimental and production-quality thrust-vectoring designs, as well as opening the door to more capable and *"intelligent"* control systems. Better materials and systems were making new and more efficient aircraft designs possible.

As a result, Dryden's work continued to embrace a diverse mix of research efforts in both atmospheric and space flight. But the pace of change, and the degree of directional shift in national priorities, projects, and aerospace direction, were accelerating. And the increasing pace of change created new challenges for Dryden's management and staff and put strains on even Dryden's historically flexible personnel and resources as the center entered the 21st century. Even before Dryden's sixth decade was out, the Access to Space initiative and related hypersonic research, which had absorbed a significant portion of the center's resources in the second half of the 1990s, had given way to a new space exploration initiative focused on the moon and Mars. The end of the close-quartered Cold War conflict in Europe, as well as improvements in missile maneuverability, lessened the military's need for highly maneuverable fighter aircraft, even as military interest in unmanned aerial vehicles (UAVs) increased. Dryden's NASA funding was also declining, causing the center to re-evaluate and refocus its work priorities and its working relationships with external agencies, universities, and industry partners.

Not all of those changes were bad, but they forced the center to once again readjust – if not completely reinvent itself – to remain a relevant and useful resource for the nation and its critical aerospace partners and needs.

Access to Space/Exploration

In the years following the Challenger accident, NASA began to look at what kind of spacecraft could or should be developed to replace the aging shuttle fleet. Clearly, a replacement would have to be found, especially if the U.S. were going to continue supporting the International Space Station. There was also pressure to reduce the cost of getting payloads into space – in part to allow NASA to reduce its budget for space flight. If the cost of accessing space could be significantly reduced, the reasoning went, it might generate more commercial applications for space technology. An increase in applications could, in turn, spark the development of a more robust commercial space technology industry, which might allow NASA to transfer more of its space flight responsibilities to private industry.

Two rather different-looking F-15 research aircraft from Dryden flying in formation during a Phase IIa nozzle-expansion (flight-control) mission of the Advanced Control Technology for Integrated Vehicles (ACTIVE). The less colorful aircraft is another F-15B. (NASA photo EC96 43656-02)

One way to make access to space cheaper was to develop more efficient, reusable launch vehicles. The space shuttle was a reusable vehicle, but it had been designed in the early 1970s and was far from efficient. By the 1990s, computer, materials, and propulsion technologies had advanced tremendously. So researchers proposed taking advantage of those improvements to design and build a far more capable and efficient spacecraft. In particular, engineers wanted to explore a possible single-stage-to-orbit (SSTO) vehicle. An SSTO design would utilize a fully reusable, single-stage launch vehicle, instead of using a multi-stage rocket system, to propel the vehicle into orbit.

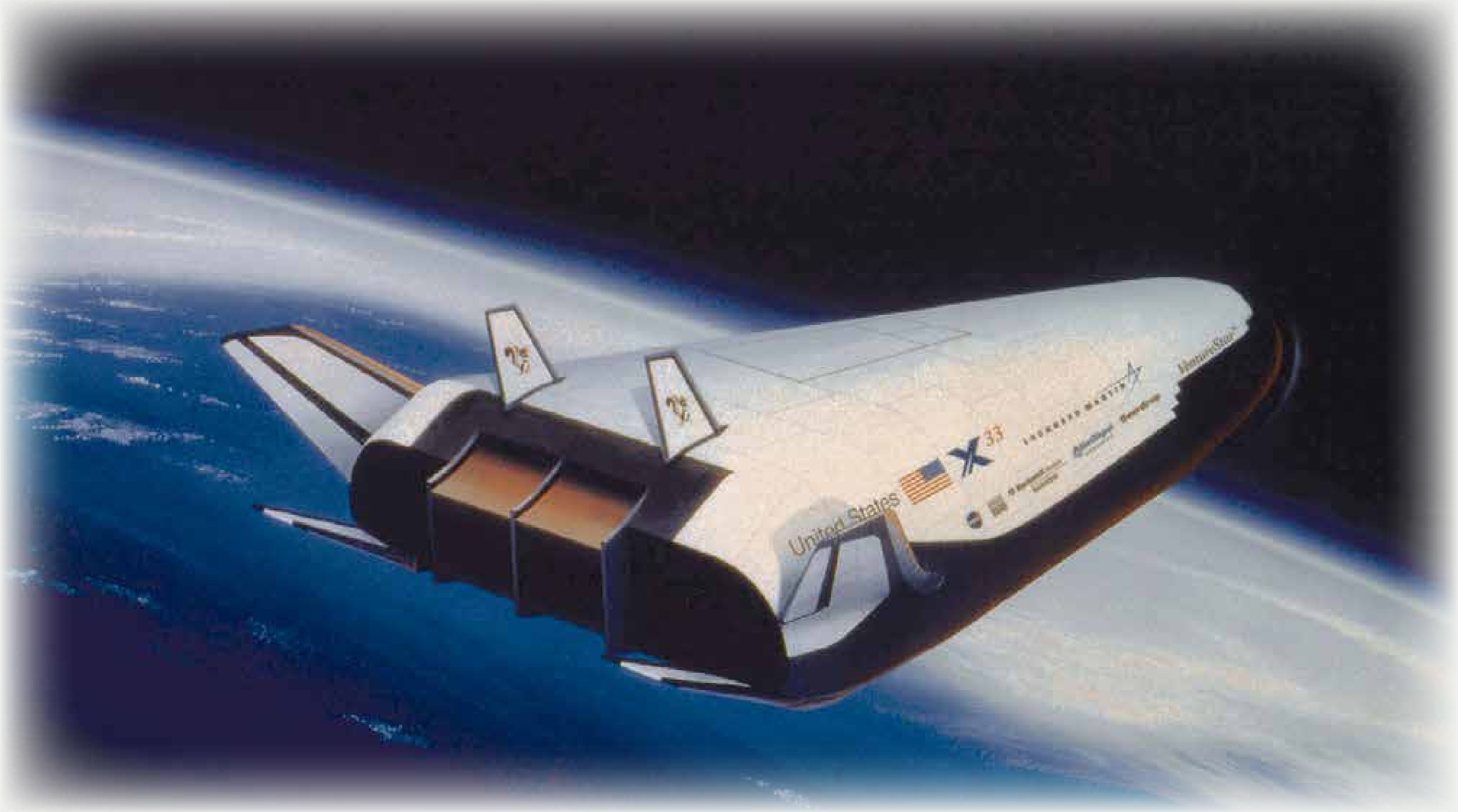
Kevin L. Petersen, NASA Dryden Center Director. He became acting director of the center on August 1, 1998, dropping the "acting" from his title upon his appointment as director on February 9, 1999. (NASA photo EC99 45142-1)

By the beginning of 1993, NASA had turned these thoughts into a formal *"Access to Space"* initiative, which laid out a two-pronged approach for developing new launch and space vehicles. An industry competition would be held for a new, Single-Stage-To-Orbit Reusable Launch Vehicle (SSTO RLV) capable of carrying humans as well as cargo. That vehicle would be used to replace the shuttle. At the same time, a second line of research was approved to explore the development of reusable launch systems for getting smaller, non-human payloads into orbit.* By developing the technologies for a single-stage rocket engine and improving the design of reusable launch vehicles, NASA hoped to reduce the cost of getting a payload into orbit by a factor of 10.

By 1996, Lockheed Martin had been selected to develop the large, crewed SSTO RLV – a lifting body design the company dubbed the *"VentureStar."* As a first step in that development effort, Lockheed Martin and NASA also agreed to work together on building a sub-scale technology demonstrator, which was designated the X-33. The X-33 was to be a half-scale, suborbital vehicle that would test some of the critical technologies for the VentureStar, including a *"linear aerospike"* rocket engine that Lockheed Martin planned to incorporate into the spacecraft.

The X-33

The X-33 program was managed by NASA's Marshall Space Flight Center, but Dryden was involved in several aspects of the research effort. Plans called for the X-33 to be launched from a site near Dryden, so the center took on various tasks related to the launch and testing of the X-33, including range safety, extended range support, and range data collection and reduction, as well as assistance in developing the launch control facility. Dryden also conducted hot thermal structures testing of components and aero-thermal calculations for the X-33's heat shields. In addition, because of all its X-plane and integrated controls research, Dryden also had a great deal of experience and expertise in developing flight control laws. So the center helped the X-33 team develop flight control laws for the new vehicle, using its specialized engineering and hardware-in-the-loop simulation facilities. The X-33 was also slated to use the flush air data system that Dryden engineers had originally developed for the center's research aircraft.



Artist concept of the X-33 advanced technology demonstrator by Lockheed Martin. (NASA photo EC96 43631-9)

The largest contribution Dryden made to the X-33 program, however, was an effort focused on the vehicle's unusual, linear aerospike engine. Traditional rocket motors have bell-shaped exhaust nozzles that give the exhaust plumes a fixed shape throughout the rocket's ascent. But bell nozzles are heavy, and a fixed-shape exhaust plume keeps the motors from operating at peak efficiency throughout most of their trajectory. So as early as the 1950s, the Rocketdyne Corporation began exploring an alternative concept called an aerospike engine. Instead of using bell nozzles, Rocketdyne's aerospike design funneled the exhaust plume out of the combustion chamber and around a concave spike. The concave curve of the spike defined half the shape of the exhaust plume, acting like half of a bell nozzle, but the outside edge of the exhaust plume's shape was controlled by the density of the surrounding atmosphere. A linear aerospike design sends the exhaust down both sides of a rectangular center form with broad, concave sides. The curved center plates defined the shape of the exhaust plume's inner edge, while the atmosphere shaped its outer edge.

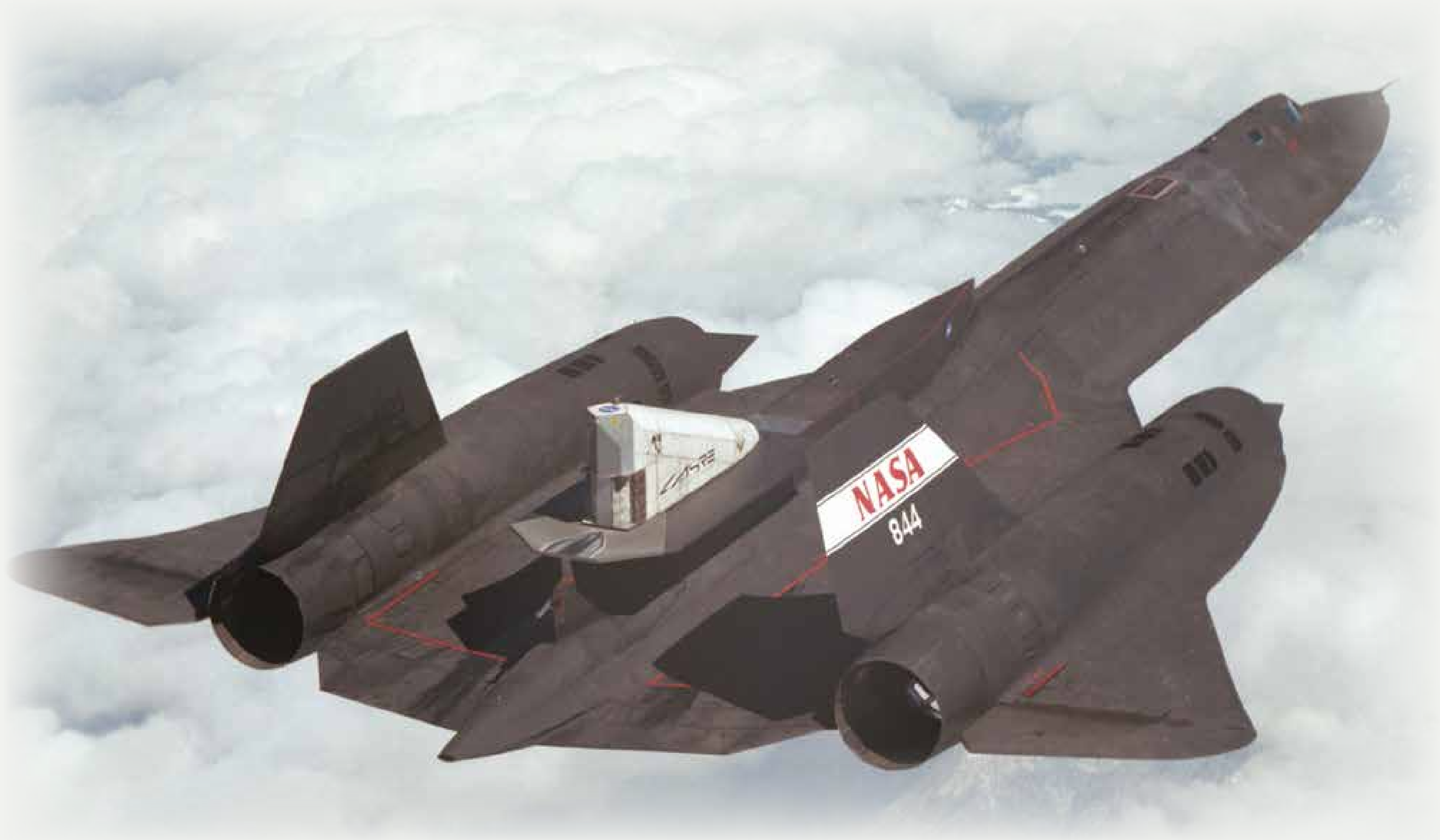
Near the ground, where the air is denser, the air surrounding the exhaust exerts more pressure against the plume, keeping its shape fairly narrow – a highly efficient shape for generating thrust. As the rocket climbs into thinner air, the surrounding air pressure decreases, allowing the exhaust plume to widen – a more efficient shape for generating thrust at higher altitudes. The center form was also designed to tilt side to side, allowing the motor to vector its thrust to help steer the craft. The simplicity and reduced hardware requirements of the design also meant that – at least in theory – an aerospike motor could be as much as 75 percent smaller than comparable bell-nozzle designs.

Clearly, a linear aerospike design offered several significant advantages for spacecraft – especially a craft attempting to reach orbit with only a single-stage motor. But in the 1950s and 1960s, the concept wasn't mature enough for use on a functional spacecraft. By the mid-1990s, however, technology had advanced, and Lockheed Martin opted to include a linear aerospike motor for its X-33 and VentureStar designs. But the engine had never been tested in realistic flight or atmospheric conditions. Designers also were unsure about what impact the aerospike's exhaust plume might have on the aerodynamics of the X-33's lifting body shape at various points along its launch trajectory.

LASRE Program

Flight research could resolve some of those uncertainties, but flight testing a representative airframe/engine combination along the X-33's launch profile would be difficult. Fortunately, Dryden had two SR-71 Blackbirds in its stable of research aircraft. The Blackbird was sturdy enough to support a heavy research model and had the high-speed and altitude capabilities to track the X-33's launch trajectory. So the center proposed mounting half of a 20 percent model of the X-33, minus its tail fins, rotated 90 degrees and equipped with eight thrust cells of an aerospike engine, on the back of a Blackbird. The SR-71 could then carry the combination, dubbed the *"canoe,"* to specific altitudes and speeds along the X-33's launch trajectory and collect data on both the engine's performance and the aerodynamic impact of the plumes on the X-33 itself.

This high-risk, but potentially high-payoff, research effort was called the Linear Aerospike SR-71 Experiment, or LASRE. The X-33/aerospike model, which stretched 41 feet in length and weighed 14,300 pounds, was mounted on one of Dryden's SR-71s in 1997, and a total of seven flights with the combination were conducted in 1997 and 1998. The program produced some valuable data from hot firings of the engine on the ground and cold flow tests in flight, but the test apparatus had persistent liquid oxygen leaks that the team was not able to track down and fix within the schedule constraints of the program. A leak in the liquid oxygen was a serious matter, because if the oxygen mixed with the system's hydrogen fuel, it could have caused an in-flight explosion – a risk that was simply too high to take. Ironically, the problem could have been fixed without too much difficulty, because the cause turned out to be a fairly simple matter of loose injectors inside the engine. But at the time that the go/no-go decision had to be made, the X-33 program schedule pressures precluded committing the time and resources to hunting down the problem. So the LASRE program was terminated in 1998, without ever hot firing the aerospike engine in flight. Subsequent ground firings and thrust-vectoring tests of a full-scale linear aerospike engine at NASA's Stennis Space Center, however, were successful. And in a small 2003 research effort funded by Dryden's *"Director's Fund"* budget – the same kind of budget that enabled the first lifting body to be built and tested behind a souped-up Pontiac – several Dryden engineers successfully tested an aerospike rocket atop a high-powered, amateur rocket.



An SR-71A flying on April 15, 1998, during a cold-flow test of a model of the aerospike engine during the Linear Aerospike SR-71 Experiment (LASRE). (NASA photo EC98 44509-13)

Clearly, the aerospike engine, in either its straight or linear configuration, had potential. But it would have to wait for something other than the X-33 to come along for its promise to be realized. For not long after the LASRE flights were discontinued, the X-33 program itself was cancelled. The original X-33 flights were scheduled to take place in 1999. But technological problems – not only with the linear aerospike engine, but also with the composite materials Lockheed Martin planned to use for the X-33's fuel tanks – caused that schedule to slip, adding to the cost of the program. With several large technical issues still unresolved, chief among them structural problems with the fuel and oxidizer tank, it was not clear to NASA managers that the technology for such an ambitious single-stage-to-orbit vehicle had matured enough to support a successful program. As a result, NASA decided not to add funds to the effort and, after several rounds of negotiations, the X-33 program was terminated in the spring of 2001.

The X-34

The X-34, which was another piece of NASA's Access to Space program, was designed to test the feasibility of launching small commercial and scientific payloads aboard a reusable, *"quick-turnaround"* launch vehicle. Like the X-33, the X-34 was a technology demonstrator, designed to flight test a number of related technologies ranging from propulsion and thermal protection systems to composite structures. The vehicle was designed and built by the Orbital Sciences Corporation, which had designed and built the Pegasus® launch system. Marshall Space Flight Center managed the X-34 program, and Dryden was selected to run the flight test portion. Dryden also contributed its Flush Air Data System (FADS) to the X-34 design.

Endeavour
United States
U.S. AIR FORCE
BOEING
SMV X-40 A

Orbital Sciences Corporation's X-34 technology demonstrator on April 16, 1999. (NASA photo EC99 44976-31

The plan was to air-launch the X-34, which measured just over 58 feet long and had a wingspan of almost 28 feet, from the same L-1011 transport aircraft that Orbital acquired to launch the Pegasus® rockets. After being dropped from the L-1011's pylon, the X-34 would then fire a single-stage *"Fastrac"* rocket engine, designed by engineers at Marshall, and climb to 250,000 feet at a speed of Mach 8. After completing its mission, the autonomous X-34 would then return to a runway landing and be prepared quickly for another flight.

A structural test vehicle arrived at Dryden in 1999, and several captive-carry flights were completed that fall, with the vehicle attached to the L-1011. But the following year, an assessment by managers at Marshall determined that the X-34 had numerous technical and hardware issues that were simply too expensive to resolve within the constraints of the program. So in the spring of 2001, the X-34 program too was discontinued.

The X-40A/X-37

The cancellation of the X-33 and X-34 programs did not, however, kill the idea of an improved reusable launch vehicle. Lower-cost access to space was still a goal that both NASA and industry wanted to achieve. So as early as 1998, NASA and Boeing began exploring the possibility of another, less ambitious demonstrator vehicle to help advance the technology associated with a reusable launch vehicle. The result was the X-37, designed to evaluate a number of new technologies in propulsion, advanced guidance navigation and control, thermal protection systems, avionics, structures, insulation, and seals, in both orbital and reentry environments. The original plans called for the building of two vehicles: an unpowered Approach and Landing Test (ALT) vehicle that would be dropped from Dryden's NB-52B mothership, and a second, orbital, vehicle that would be carried into space, released, and flown back to a runway landing.

To reduce the risk of this ambitious research effort, however, X-37 program managers took two additional steps. First, they based the X-37 on a previous design Boeing had developed for the U.S. Air Force's Space Maneuver Vehicle (SMV) research program in the late 1990s. The X-37 was, in essence, a larger version of the Air Force's X-40A. Second, NASA and Boeing arranged to borrow the original X-40A test vehicle from the Air Force to conduct preliminary flight tests and collect aerodynamic and control law data through a series of research flights at Dryden before proceeding with the full-scale X-37 design.

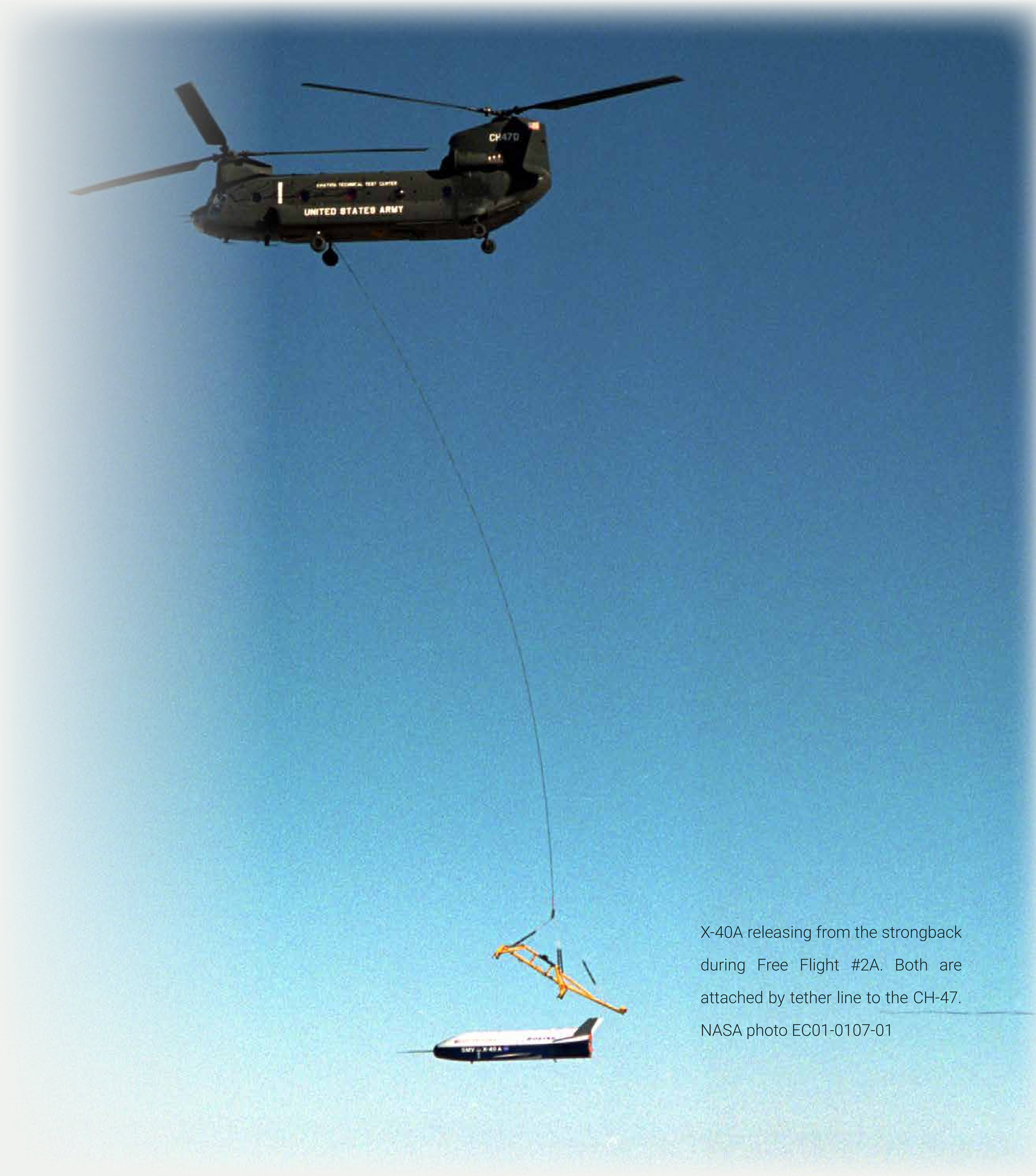
The X-40A/X-37

The X-40A arrived at Dryden in 2000 and, after ironing out some initial problems, the team completed seven X-40A flights before the program ended in 2001. For each flight, the X-40A was carried aloft by an Army CH-47D Chinook helicopter and released from an altitude of approximately 15,000 feet. The X-40A used onboard navigation and landing systems to guide itself back to a runway landing.

The X-40A flight program was very successful. But by the time the X-40A flights were finished, the X-37 program plans and budget had changed. Initially, the goal was to carry the X-37 into orbit aboard the space shuttle. But due to cost and schedule problems with the shuttle, managers soon decided to use an expendable launch vehicle instead. Continuing budget concerns then limited the program to suborbital flights, and NASA eventually withdrew its funding for the program. By 2005, DARPA had taken over from NASA the now vastly scaled-back X-37 program. The X-37 did finally conduct an ALT in the spring of 2006, but Dryden's involvement was limited to providing range safety and tracking services to DARPA for the flight.

Orbital
X-34

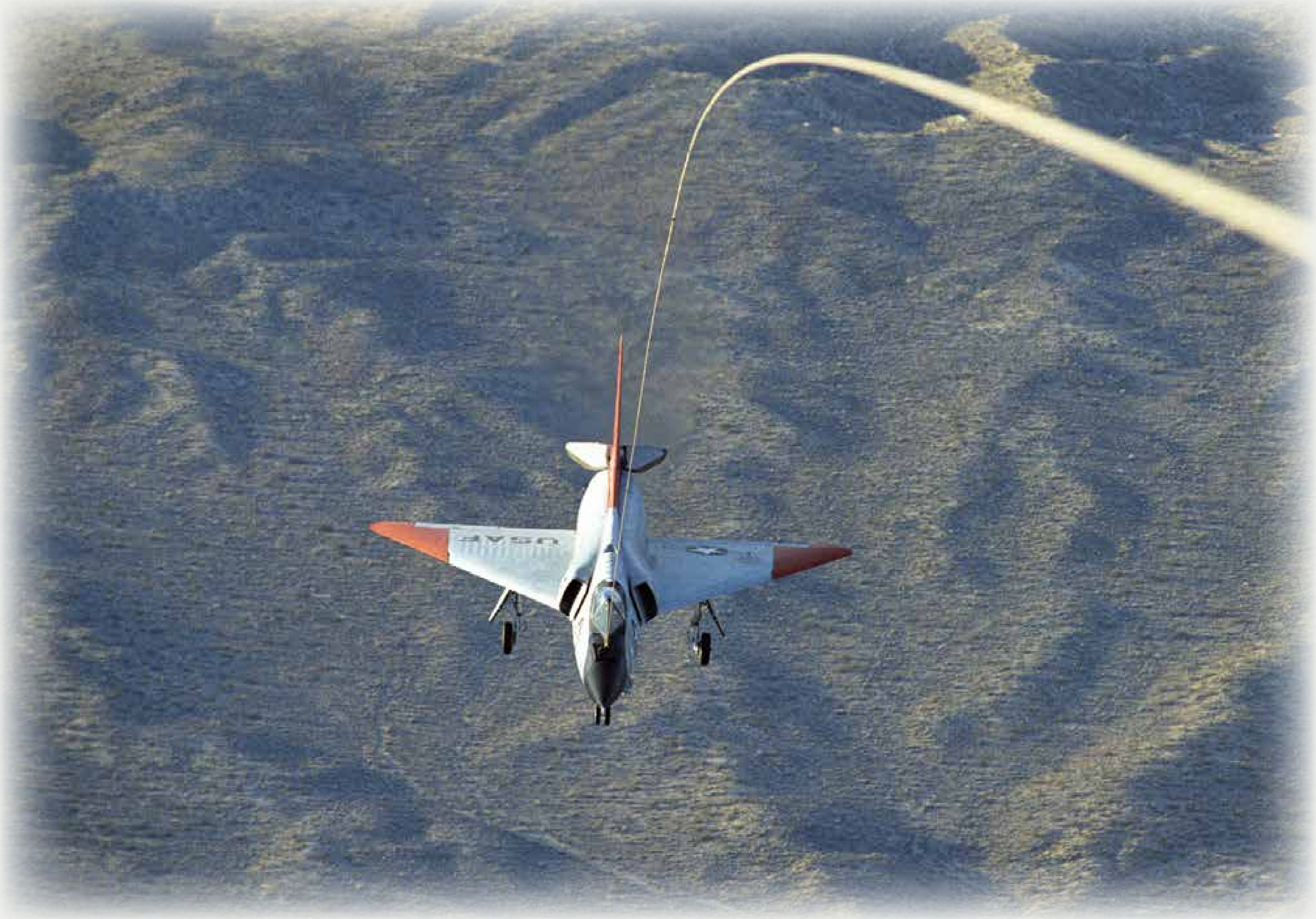
The Boeing X-40A on the Dryden Ramp while Endeavour is towed toward the MDD following its landing at Edwards, May 1, 2001. (NASA photo EC01 150-5)



X-40A releasing from the strongback during Free Flight #2A. Both are attached by tether line to the CH-47. NASA photo EC01-0107-01

The Eclipse Program

Of all the reusable launch vehicle technologies and concepts explored by NASA and its industry partners in the late 1990s, one of the more unusual was an idea put forth by Kelly Space & Technology (KST) for towing a vehicle up to its initial launch altitude. Kelly had conceived an idea for an *"Astroliner"* launch vehicle that would be towed behind a Boeing 747 to about 45,000 feet. At that point, the Astroliner would cut loose and fire its engine, climb to the target altitude for releasing its payload, and glide back to a runway as either a remotely piloted or autonomous landing vehicle.



The Eclipse program's QF-106 being towed behind a C-141A on its third flight, January 23, 1998. (NASA photo EC98 44393-52)

Kelly had gotten a small amount of funding from NASA to explore how such a towed configuration would behave. The company initially contacted Dryden to inquire about using NASA's 747 Shuttle Carrier Aircraft. But the flight test program developed by Dryden and KST involved towing a Convair QF-106 behind an Air Force C-141A Starlifter. The F-106 was chosen as a test aircraft because its delta wing configuration was similar to KST's proposed Astroliner.

Towing a fighter plane behind a large cargo aircraft was a highly unusual flight research project, but Dryden actually had some experience in towing research aircraft, having towed the original M2-F1 lifting body behind a Pontiac, DC-3, and an R4D. In addition, Mark Stuckey, the NASA research pilot chosen to fly the F-106 for the Eclipse project, had learned a lot about the dynamics of air-tow vehicles from towing hang gliders in his free time.

Stuckey flew the F-106 in a *"low tow"* position behind the C-141. He kept the F-106's engine running in case he needed to cut loose and fly the fighter away from the tow aircraft, while deploying the F-106's speed brakes to simulate the drag of the Astroliner launch vehicle. On one flight, the F-106 was accidentally cut loose early, but the other five test flights were all highly successful. Kelly did not, in the end, develop its Astroliner concept, but the Eclipse flights proved that a towed aircraft concept was at least a viable design option.

The X-38

The X-33, X-34, X-37, and Eclipse programs all focused on reusable launch vehicle technology. But Dryden was also drawn in as a flight test partner for another NASA spacecraft design effort in the late 1990s – one whose sole mission was to bring International Space Station astronauts home safely in an emergency. As a result, the X-38, or Crew Return Vehicle (CRV), was designed to fly and land without a pilot on board. The shape chosen for the X-38 was a lifting body because an emergency return vehicle needed good cross-range capability. But the X-38 added an unusual twist to the typical lifting body configuration. Instead of landing on a runway, the X-38 was designed to deploy a steerable parachute during the final portion of its descent, increasing the number of potential landing sites and eliminating the need for a skilled, or even conscious, pilot on board.

The X-38

Dryden had explored the concept of an autonomously flown parachute recovery system for a spacecraft in the early 1990s with a remotely piloted model called the *"Space Wedge."* While it was a small effort involving a model aircraft dropped first from an ultralight aircraft and then from a Cessna 206, the Space Wedge research was supported in part by the Army, M.I.T.'s Draper Labs, and NASA's Johnson Space Center – evidence that there was external interest in exploring the utility of the idea. Indeed, by 1995, the Johnson Space Center had begun design work on the X-38.

JSC had several goals with the X-38 program. First, there was a clear need to design a crew return vehicle for the ISS. But the center also wanted to see if it could substantially reduce the cost of developing a new spacecraft by using as much existing technology as possible, while bringing more of the project work inside NASA to refresh and sharpen the practical design and construction capabilities of the engineers at the space center.

United States
X-38 V-132

X-38 vehicle V-132 on the Rogers Dry Lake on March 30, 2000 following its successful descent under a gigantic parafoil. (NASA photo EC00 0097-09)

To mitigate both the cost and risk of designing a completely new vehicle, JSC chose to model the X-38 after the successful X-24A lifting body – literally. The X-24A had been flown at Dryden in the late 1960s and early 1970s, and one of the vehicles, an SV-5, was still on display at the U.S. Air Force Academy in Colorado. The X-38 team made a splash mold of that vehicle and had Scaled Composites make two fiberglass airframes from the mold for the X-38 flight research program.

The Johnson team brought the vehicles to Dryden to conduct a series of flight tests with the vehicle/parachute combination, using Dryden's venerable NB-52B mothership as a launch platform. But the center's NB-52B wasn't the only reason JSC managers wanted to bring the project to Dryden. They also knew that Dryden had an incredibly strong heritage not only in flight test, but also in flight control law development, which would play a large role in the X-38's success. In addition, Dryden had ground facilities, including a structural loads laboratory, that could augment the research and testing the team had done at Johnson.

But taking a concept to flight quickly exposes unanticipated difficulties with a technology or system, as the X-38 team, like many before them, soon discovered. The early days of the X-38 flight research effort were anything but smooth. The team began by testing the concept with a 1/6-scale model of the X-38 dropped from a small airplane – tests that went fairly well. But then the problems started. The pyrotechnic system to deploy the parafoil on the full-scale vehicle wouldn't work properly in cold-soak tests aboard the NB-52B. In hunting down the cause, the team discovered that they'd been given faulty data on the system's fiber optic cables, which had led them to install undersized cables in the vehicle. On one of the early parafoil flight tests – shoving a crude test vehicle and parafoil combination out the back of a C-130 cargo plane – the straps tying the combination to the cargo pallet wrapped themselves around the test vehicle and ripped the parachute off the model. Two of the electro-mechanical actuators used to deflect the X-38's body flaps, which worked fine on the ground, overheated and melted while in the C-130's cargo bay because there wasn't enough cooling air at altitude to compensate for the heat they generated. And on the first flight of the X-38 vehicle with a 5,500-square-foot parafoil, a panel ripped out of the chute, causing the team to stand down on further flights for almost a year while they ironed out the technical problems with the parachute system and other components.

NASA
United States

An X-38 Crew Return Vehicle under the wing of the NB-52B mothership on November 19, 1997. (NASA photo EC97 44319-08)

The X-38

The team returned to the air in February 1999, but after only one more flight on the first X-38 vehicle, the team sent it back to Scaled Composites for redesign work – not because the original design was faulty, but because the mission requirements had changed. Originally, the plan had been to carry the X-38 to the International Space Station aboard the shuttle. But the X-38, just like the space station itself, was an international effort. And the European Space Agency, which joined the X-38 team in 1996, wanted to launch the craft on top of an Ariane 5 rocket. So the X-38 team had to modify the vehicle to accommodate that requirement.

Meanwhile, the team conducted several successful flights of the second X-38 vehicle, with a 5,500-square-foot parachute, in 1999 and 2000, and the redesigned first test vehicle returned to Dryden in the summer of 2000. Finally, in November 2000, the team attempted to fly the redesigned X-38 vehicle and the full-sized, 7,500-square-foot parachute together for the first time. The components had all been well tested, and all seemed in order. But once again, the flight showed just how different results can be in flight when whole systems and real-life conditions come together for the first time.

Immediately after launch, the X-38, which was supposed to roll only 30 degrees laterally before restabilizing itself, did a complete, 360-degree roll. Then, the pyrotechnic releases for the parafoil's drogue chute fired slightly out of sync, causing the vehicle first to pitch up, and then violently forward as the main chute deployed. The vehicle recovered and landed safely, but the incident prompted several important changes in the X-38's hardware and software. Part of the roll had been caused by the fact that the X-38 test vehicle was a hand-made prototype. One fin, it turned out, was three inches different from the other. But the control law responses were also set too high, exacerbating the problem.

After sorting out those difficulties, however, the X-38 went on to achieve a high level of success. The parachute proved a reliable landing system, and the vehicle demonstrated good flight characteristics. The systems were working flawlessly, and a space-flight version of the X-38 was 85 percent complete when the project was cancelled in 2002. NASA had decided to refocus its efforts on a project called the Orbital Space Plane – a vehicle that could be both a launch and recovery spacecraft. The Orbital Space Plane program was itself cancelled less than two years later, however, when President George W. Bush announced a new initiative to return humans to the moon and go on to explore Mars – a goal that favored the use of a capsule-shaped spacecraft over a lifting body or winged design.

The X-43A

But the X-38 program was an excellent example of successful budgetary management of a spacecraft development project. It also clearly illustrated the importance of flight research in advancing aerospace technology and concepts – and the importance of a flight research facility with a long history of experience and expertise to bring to that process. The components of the X-38 worked well individually, on the ground. But when they were combined and exposed to the pressures of altitude, speed, and atmospheric flight dynamics, all sorts of discoveries were made, as Dryden engineers like to say. But through that process, the critical problems were identified and ironed out, leading to a final product that exceeded expectations and generated important data and design knowledge. The X-38 wasn't successful in the sense that it had no problems, but because the system of researching that concept and those problems in flight worked exactly as it is meant to. And in that process, the expertise of Dryden members of the team, not only in terms of flight test operations, but also in flight control-law development and effective troubleshooting, was invaluable.

Most of the space-related research efforts in the 1990s and early years of the 21st century, both at Dryden and at NASA in general, involved rocket-propelled spacecraft. But in 1996, Dryden and the Langley Research Center paired up to explore an alternate propulsion system that might make access to space easier and more cost-effective. The concept was a supersonic combustion ramjet, better known as a scramjet. A ramjet, from which the scramjet derives, is an air-breathing engine that uses the high speed of a craft moving through the air, instead of turbine blades, to compress the air needed for combustion. That air is forced into a chamber, mixed with fuel, ignited, and the exhaust generates the thrust for flight. There are no moving parts in the engine. A scramjet can operate at both supersonic and hypersonic speeds, but is fundamentally different from a ramjet. At supersonic speeds ramjets must decelerate the air to subsonic speed inside the engine inlet before combustion takes place. Airflow in a scramjet engine remains supersonic throughout its entire passage in the engine chamber, including the combustion itself. Successfully running a scramjet has been likened to burning a match in a hurricane, which is an understatement.

Yet scramjet technology has long appealed to researchers because a scramjet-powered vehicle could have significantly greater payload capacity than a traditional rocket-propelled craft. A traditional rocket motor, after all, has to carry both its fuel and oxidizer on board, while a scramjet draws oxygen from the surrounding atmosphere to burn with its fuel.

A Dryden control room during an X-43A cative-carry mission to prepare for the upcoming Mach 9.6 flight. (NASA photo EC04 266-3)

The idea of a scramjet engine for high-speed flight was not new in 1996. Engineers at NASA as well as in industry had, as far back as the 1960s, envisioned a scramjet and went so far as to fly a dummy engine on an X-15. Plans to operate an actual engine never advanced, however, and the X-15 program ended in 1968 – the only aircraft at the time that flew hypersonically. Two decades later plans for the X-30 National Aero Space Plane in the late 1980s called for it to be powered by a scramjet engine. But the X-30 also incorporated many other radically new technologies. When that project was cancelled some NASA researchers wanted to attempt a more realistic research effort that would prove the feasibility of just the scramjet concept.

Hypersonic flight and scramjet propulsion are both challenging areas to explore: the best any wind tunnel could do was create flight conditions for the full-scale X-43 at Mach 7 for just over 11 seconds. Mach 10 data came one-thousandth of a second at a time. Scientists in Russia and Australia conducted some scramjet research and had even flown simple scramjet engines, but nobody had ever combined a working scramjet engine with a hypersonic test vehicle in real-world flight conditions. As Dryden propulsion engineer Dave Lux put it, *"getting a scramjet to work is a feat. Integrating a scramjet into a vehicle and proving that the thrust-to-weight ratio is workable is amazing."*[1]

The X-43A

By undertaking their ambitious joint research effort, Langley and Dryden hoped to achieve that "*amazing*" goal. The official mission of the eight-year *"Hyper-X"* program (for hypersonic experimental) was to investigate and demonstrate advanced high-speed propulsion concepts that could make air-breathing, hypersonic flight possible. Langley spearheaded the technology development, and Dryden led the flight research of the program's test vehicle, which was designated the X-43A.

Hyper-X was a difficult project to manage, not only because of the challenging nature of the research, but also because the suppliers for the program were scattered from California to New York. The vehicle itself, which was essentially a scaled-down version of the design McDonnell Douglas submitted for the X-30, was 12 feet long, and weighed 3,000 pounds. The reason for the X-43A's heavy weight was that part of the airframe was built out of solid steel to make it as rigid as possible, and the nose section was a large slab of tungsten, mostly to maintain the craft's center of gravity. The vehicle's shape was not an afterthought, but an integral part of the engine itself, helping to ram the air into the engine and then providing an exhaust expansion shape for greater thrust. This is what they meant by an integrated scramjet.

Plans called for the X-43A to be attached to the nose of a Pegasus® rocket booster and released from Dryden's NB-52B mothership. The Pegasus® booster would then lift the X-43A to its test altitude of 100,000 feet and accelerate it to its test speed of either Mach 7 or Mach 10. At that point, the X-43A would separate from the rocket booster, light its internal engine, and proceed under its own power for a few precious seconds of data-producing flight before burning through its fuel and descending into the Pacific Ocean.

By June 2001, the X-43A, built by MicroCraft (later ATK-GASL), had arrived at Dryden and was ready for its first flight. It was a disappointingly short flight. Just a few seconds after being launched from Dryden's NB-52B, the Pegasus®/X-43A *"stack"* deviated from its course and had to be destroyed. Researchers finally determined there were a number of errors in the modeling of the control system and aerodynamics that failed to predict that the lower, slower launch would exceed the booster's control capacity (forces at that altitude deflected the fins beyond the control system's ability to manipulate them). The booster became unstable shortly after launch; its fins ripped off, and the stack went out of control.

A modified Pegasus® rocket ignites moments after release from the NB-52B, beginning the acceleration of the X-43A over the Pacific Ocean on March 27, 2004. (NASA photo EC04 0092-32)

The X-43

Figuring out how to fix those problems took the team almost a year and a half. In the end, researchers modified the booster's fin actuation system to increase its torque, reworked the control laws, and made the decision to launch the next X-43A from a higher altitude to reduce the atmospheric pressure on the booster/X-43A combination after launch. But since the X-43A still had to separate from the booster at 100,000 feet, launching the Pegasus® from a higher altitude meant that the booster needed to carry less fuel to provide a Mach 7 burnout speed. And the team only had two more booster rockets to launch the two remaining X-43A vehicles. They couldn't afford to expend one proving the safety and efficiency of removing a portion of the booster's fuel.

After intensive analysis, and persuasive arguing, the X-43A team convinced NASA Headquarters to let it proceed with the X-43A flights without a separate booster test. And on 27 March 2004, the team was vindicated. The Pegasus® booster performed flawlessly, and at the stack's peak altitude the X-43A separated, lit its scramjet engine, and accelerated under its own power for 11 precious seconds of powered, hypersonic flight, reaching a speed of Mach 6.83. The flight marked new speed records for both an air-breathing engine, which had been previously held by a ramjet-powered missile that had gone just over Mach 5, and an air-breathing aircraft/engine combination. The previous record for an air-breathing engine had been set by a ramjet-powered missile traveling just over Mach 5, and the record for an airframe/engine combination had been held by the SR-71, at just over Mach 3.2.

Eight months later, the third X-43A shattered even the rocket-propelled aircraft speed record of Mach 6.7, which had been set by an X-15 in 1967. The X-43A reached a top speed of Mach 9.6, or almost 7,000 mph, and flew under power for nearly 11 seconds, yielding tremendous data to those on the ground. And while there was no pilot on board the X-43A, the flight was not without its drama. The night before that flight, as the crew was fueling the X-43A with hydrogen under 8,500-psi pressure, cold desert winds began gusting to almost 60 miles per hour. Every available sandbag was drafted into service to keep the equipment stable during the volatile fueling process. But by 7:00 in the morning, the weather had calmed into perfect launch conditions.

It took hundreds of people to make the two flights possible. The barriers the X-43A broke and the knowledge it sent home were staggering. In addition to incalculably valuable real-world data on both hypersonic flight and scramjet technology, the X-43A conclusively proved that a scramjet-powered vehicle could, in fact, work. The X-43A flight research also proved, once again, the value of flight in any aerospace research effort. Computer models and simulations can be inaccurate. Nature and physics never are. But the only way to correlate model or simulation data with those hard and fast benchmarks of the real world is to test that data in the real world.

Initially, the Hyper-X team had hoped to continue its hypersonic and scramjet research with a larger, more capable vehicle. But with NASA's change in focus to the exploration of the moon and Mars, the team couldn't find support or funding for follow-on research. Nonetheless, just as X-15 and X-30 data helped the Hyper-X team design and build the successful X-43A, the data generated by the X-43A is now part of the nation's knowledge base – available for the next round of explorers to use whenever the need arises for researchers to push the boundaries of aerospace capability yet another step higher, faster, and farther.

Other Space Support

While Dryden's work with NASA's various X-plane projects constituted the largest portion of its space-related research over the course of its sixth decade, the center also provided support for the nation's space program through other services and smaller research efforts.

One such effort was the *"Inflatable Wing"* project the center undertook in the late 1990s. Envisioned as a potential technology for a Mars or other planetary exploration aircraft, the basic concept was simple: Find a way to fold and package wings inside a more suitable shape for launch and interplanetary travel. Then develop a method to extract and inflate the wings once in the planet's atmosphere, creating a flyable aircraft capable of exploring the planet more efficiently and with a different perspective than either a ground vehicle or an orbiting spacecraft could manage.

High-Speed Research

The execution of that concept, of course, was a lot more problematic. But it was the sort of challenge that Dryden's innovative model and aircraft-building, hands-on hardware engineers relished. A small group of Dryden personnel started with folding, inflatable prototype wings from the U.S. Navy that were part of a small UAV originally designed to be gun-launched before deploying, to create an observation aircraft. The Dryden group then designed two small aircraft models on which to test the wings – a basic model called the I-2000 and a variant of the X-24A lifting body. And in the venerable tradition of Dryden's homegrown project ingenuity, the engineers used a regulator and valve from a low-cost paintball gun to create a pyrotechnic system to deploy the wings – leading to some interesting questions from the accounting department about purchases from a place called *"Paintball Paradise."*

The F15-B flying a Lifting Insulating Foam Trajectory (LiFT) experiement on its flight test fixture on February 14, 2005. (NASA photo EC05 0028-18)

The span of the inflatable wings was just over five feet, but when not inflated, the wings fit in a canister the size of a small coffee can. There were some small glitches in the system to be worked out in future experiments, but much to some observers' surprise, the system worked. The concept has not been pursued beyond Dryden's initial research effort. But as one of the project engineers said of the center's innovative effort, *"We took the 'giggle factor' out of the concept."*[2]

Among Dryden's other space-related research efforts was the development and testing of a space-based telemetry system for use with a next-generation launch vehicle. Dryden also continued to act as an alternate landing site for NASA's shuttle program and provided extra support and assistance after the 2003 Space Shuttle Columbia accident. Initially, the center helped search for debris with one of its ER-2 high-altitude aircraft. Then, as part of NASA's return-to-flight effort, Dryden conducted a series of flight tests with its F-15B testbed to research the behavior of insulation foam divots dislodged from the shuttle's external tank during launch, the cause of the Columbia accident. The F-15B was chosen for the Lifting Insulating Foam Trajectory (LIFT) experiments because it could duplicate the shuttle's Mach numbers, dynamic pressure, and aerodynamic Reynolds numbers during its initial ascent. In addition, the aircraft already had a specialized flight test fixture beneath its belly that was ideally suited for the research.

After coating the F-15's flight test fixture with the same kind of foam used on the shuttle's external tank, and devising an effective method of expelling divots from that foam in flight, Dryden researchers flew a series of highly instrumented and documented flights with the plane to test the foam's behavior. They determined that pieces of the shuttle's foam insulation tended to stay together and were far more aerodynamic than researchers had initially thought. This finding was significant, because it meant the divots might inflict more damage than earlier estimates had predicted. That data helped the NASA team working on the shuttle's return-to-flight effort develop appropriate preventative measures to keep another shuttle orbiter from suffering Columbia's fate.

High-Speed Research

As Dryden approached its 50th anniversary, the high-speed flight research that had been the hallmark of the center in its formative years saw a resurgence, due to NASA's High Speed Civil Transport (HSCT) program. One of the most critical issues for any supersonic transport, of course, was the impact of its sonic boom on the population beneath it. So in 1996, Dryden conducted a series of flights to map the sonic boom of an SR-71 Blackbird. The experiments used an F-16XL research aircraft flying in trail behind the Blackbird to collect data on the SR-71's sonic boom in both straight and maneuvering flight. Researchers hoped that data would give them a better understanding of sonic boom characteristics as the shock wave propagated toward the ground. In 1997 and 1998, the center also teamed up with Russian researchers to conduct a series of flights with a Tupolev Tu-144 supersonic transport to collect in-flight data on a number of the plane's systems and its overall handling qualities.

During that same period, Dryden conducted a small hypersonic research project with Orbital Sciences' Pegasus® launch vehicle. Dryden researchers manufactured a special, nickel-plated steel test glove for a section of the Pegasus® booster's wing and attached the glove to a wing for one of the booster rocket's regularly scheduled missions. The glove allowed researchers to collect data on hypersonic airflow over the wing – important data for the design of any extremely high-speed civil transport or space plane.

Shown here on a mission in 1996, F-16XL #849 also flew behind an SR-71 Blackbird to collect data on the Blackbird's sonic booms during both maneuvering and level flight. (NASA photo EC96 43508-10)

But in 1998, national aerospace priorities shifted again, and the HSCT program was cancelled, eliminating both the support and the rationale for expanding any high-speed research efforts – at least at that time. Nevertheless, Dryden still found itself with plenty of work to do. Because even as the focus on high-speed civil transport receded, opportunities were expanding in other exciting and challenging research areas, including integrated aircraft systems, advanced aerodynamic concepts, atmospheric research, and unmanned aerial vehicles.

Integrated Systems and Controls

Between 1985 and 1995, Dryden had been involved in groundbreaking research into integrated, computerized flight and engine controls, including its work with its F-18 HARV and X-31 programs. But the thrust-vectoring systems on those aircraft were very basic, experimental designs. The heavy paddles used on the F-18 HARV and the X-31 weren't practical for production aircraft. An operational aircraft would need a more refined approach to vectoring-nozzle technology to achieve the kind of 360-degree thrust vectoring that the X-31 had demonstrated, with all of the potential advantages that would come from that capability. No such engine existed in the mid-1990s, but Pratt & Whitney was interested in exploring a gimbaled-nozzle concept that might lead to a viable design. Like the first electronically controlled engine, the Pratt & Whitney *"pitch-yaw balance beam nozzle"* (PYBBN) concept was high-risk, so NASA agreed to work with the company on a flight research program to explore and develop the technology further.

The result was the Advanced Control Technology for Integrated Vehicles (ACTIVE) research program, a joint effort of Dryden, Pratt & Whitney, the Air Force, and the Boeing (formerly McDonnell Douglas) Phantom Works. First, Pratt & Whitney modified two of its F-100 engines with the experimental, gimballing nozzles. The modified engines were then installed in a highly specialized McDonnell Douglas F-15 that the Air Force had used for a Short Take-Off and Landing (STOL) research program in the late 1980s but agreed to loan to Dryden for the ACTIVE research effort. The aircraft was particularly well suited for integrated systems research because it already had been modified with a quadruple-redundant digital fly-by-wire system.

Integrated Systems and Controls

The F-15 ACTIVE made its first flight in February 1996 and the first phase of its research focused on Pratt & Whitney's gimbaled-nozzle technology. But in addition to researching the nozzle technology itself, the ACTIVE program also looked at what other benefits a more production-like thrust-vectoring engine might create, including improved fuel efficiency and engine performance. One of the follow-on experiments conducted with the F-15 ACTIVE was an effort spearheaded by NASA's Glenn (formerly Lewis) Research Center that built on Dryden's previous Integrated Propulsion Control System (IPCS), Digital Electronic Engine Control (DEEC), and Highly Integrated Digital Engine Control (HIDEC) research. The High Stability Engine Control (HISTEC) research used real-time estimates of engine inlet airflow turbulence, combined with the aircraft's advanced engine control system, to maintain an ideal performance margin in the engine at all times, regardless of disturbances or flight condition. In addition to increasing the efficiency of the engine, HISTEC technology offered improvements in safety, because it could prevent sudden engine compressor stalls.

The F-15 ACTIVE researchers had wanted to take their investigations of thrust vectoring into the realm of new, highly maneuverable fighter aircraft designs that would depend on thrust vectoring for their stability, but by the late 1990s, highly maneuverable fighter technology wasn't as high a priority in the military as it had been a decade earlier. As a result, those follow-on research ideas were shelved – at least for the moment.

In 1999, however, the program did take advantage of the F-15's extremely flexible control systems to explore a more advanced, integrated *"intelligent"* flight control system. The Intelligent Flight Control System research focused on integrating flight and engine controls in a *"neural network"* that could sense the difference between what the aircraft should be doing for given control and engine inputs and its actual behavior, and then adjust control and engine inputs accordingly. A fully operational neural network could also *"learn"* from those adjustments and responses how to continue combining those controls for ideal aircraft operation. In addition to improving an aircraft's efficiency, an intelligent flight control system could allow the safe return of an aircraft that otherwise might be uncontrollable after experiencing a major system failure or other serious damage.

F-15 Advanced Control Technology for Integrated Vehicles (ACTiVE) research vehicle in flight on March 29, 1996, during the early portion of its flight research, which concentrated on gimbaled-nozzle technology. (NASA photo EC96 43485-13)

Using software developed at NASA Ames and the Boeing Phantom Works, initial flights in 1999 tested a neural network that had *"pre-trained"* responses, based on wind-tunnel data for the F-15. A second round of flights in 2002 developed algorithms, based on the aircraft's responses to flight control inputs, to enable a *"smart"* neural network to evaluate the aircraft's actual versus ideal behavior and adjust inputs accordingly. The third stage of the research, completed in 2005, tested the ability of the network to use those algorithms to *"learn"* and improve its control inputs real-time.

With this level of intelligent system, even researchers couldn't be sure exactly how the aircraft would choose to compensate for deficiencies. The system would decide for itself how to combine remaining systems and surfaces to achieve optimum handling and performance and then execute those adjustments. But the technology held great promise. Intelligent flight control systems capable of identifying patterns of aircraft response and correcting for damage or system failures, without even having to identify exactly what failures had occurred, could be an immeasurable aid to both safety and efficiency in future aircraft designs. This research was continuing even as this book went to press.

Aerodynamics/Efficiency

Integrated controls were not the only way to improve an aircraft's efficiency, however, and Dryden undertook several research efforts in the late 1990s to explore other approaches to achieving that goal. Some projects looked at new aerodynamic shapes and systems for aircraft, while an experiment in autonomous formation flight looked at navigation and flight control systems that could enable cargo aircraft to fly safely in close formation to save fuel.

Active Aeroelastic Wing

In the 1980s, Dryden participated in a research program called the Mission Adaptive Wing (MAW) that changed the camber, or curve, of an F-111's wing to adapt it better to different stages of flight. In the mid-1990s, DARPA, the Air Force, and NASA revisited that basic concept with a research effort called the Active Aeroelastic Wing (AAW). The goal of the AAW program was to explore the use of lighter-weight, flexible wings for improved maneuverability, efficiency, and weight savings in high-performance military aircraft.

The F-18 was chosen for the research because the fighter had originally been designed with lighter-weight wings. But in early test flights, deflecting the fighter's ailerons at supersonic speeds caused the lighter wings to twist, leading to poor roll performance and potential roll reversal problems. So the F-18's wing structure was beefed up considerably in all production models. The pre-production F-18 wings were perfect, however, for the AAW research. Experimenters outfitted the wings with eight separately actuated wing control surfaces (ailerons and leading-edge flaps) that could be moved to "warp," or twist, the outer wing panels up to five degrees for roll control.

Wing warping was actually the original method of aircraft control used by the Wright brothers, although it soon gave way to the use of ailerons as a more effective way to control an aircraft's roll. The AAW program wanted to explore wing warping again, however, in the hope that the technique might lead to lighter, higher-aspect wings on future aircraft. Thinner, lighter wings, in turn, could decrease drag and increase fuel efficiency, and therefore extend either the range or payload of future designs. Clearly, flying the F-18 with lighter-weight, more flexible wings raised structural concerns, so the Dryden team spent six months conducting structural load tests in the center's Flight Loads Laboratory (FLL) before signing off the concept for flight. There was also some concern about the control laws that Boeing and Dryden had each developed for the experimental aircraft. So in the end, a combination of both partners' control laws was used for the flight tests.

The AAW flights began in 2002 and continued through the spring of 2005, and the results were encouraging. Using the aeroelastic wing alone, without any differential stabilator movements, the F-18 demonstrated rolling performance close to that of a production F-18, and there were no structural problems or issues with the configuration. It's too soon to say how or when this technology might be applied, but the AAW flights demonstrated the feasibility of the concept, and led to further development work on flight control laws that would be necessary for anyone considering an aeroelastic wing as part of a future aircraft design.

Blended Wing Body/Morphing Aircraft

Another research effort into a new, and hopefully more efficient, aerodynamic shape was the Blended Wing Body effort initiated by the Langley Research Center in the late 1990s. The concept, geared toward a future airliner design, combined the characteristics of a flying wing and a conventional airliner to create a 450-passenger aircraft that, because of its more efficient wing/body shape, could still operate off of existing runways. The first step in the blended wing body research was to build a small, remotely piloted model of the design, and Dryden was enlisted to help develop the flight control software and conduct both simulation and actual flight tests of the vehicle. The project, however, was cancelled before the test model was ever completed or flown, although the concept was revived in 2006.

AFF/AAR

Two F/A-18s in the Autonomous Formation Flight (AFF) program with smoke benerators operating to show the paths of wingtip vortices. (NASA photo EC01-0328-28)

Around the same time, NASA Administrator Daniel S. Goldin announced a goal for the agency of developing a *"morphing"* aircraft that could combine some of the efficiency-oriented technologies that NASA aeronautical engineers had been working on with partners, including aeroelastic wings and thrust vectoring. While neither the blended wing body design nor highly adaptable, *"morphing"* aircraft technology have reached the stage of application yet, the discussion and initial steps toward those goals are an indication of just how far technology has come. With ever more adaptable aircraft and flight/engine control systems, new concepts and configurations that would have been unthinkable, or at least impractical, in earlier years, are now possible. The technology is being developed and tested, piece by piece. Now, all that awaits is a need urgent enough to drive the further development and integration of those technologies into a next-generation aircraft design.

AFF/AAR

Another efficiency-oriented concept conducted at Dryden in the late 1990s focused more on aircraft operation than aircraft design. The Autonomous Formation Flight (AFF) research, a combined effort among Dryden, Ames, Boeing, and UCLA, integrated satellite navigation with precise, onboard measurements of an aircraft's movement into an automatic flight control system to support close-formation flight between two aircraft. Close-formation flight could yield benefits in efficiency by reducing drag on the trailing aircraft. In the same way that a flock of geese can save energy flying in close formation behind a single leader at the apex of a V, an aircraft flying close formation behind another can use the wingtip vortices off the lead aircraft to fly much more efficiently. The lead aircraft's wingtip vortex creates an uplifting wave that lowers the thrust required by the trailing aircraft, thereby lowering the amount of fuel burned.

The problem with flying in another aircraft's wingtip vortices, however, is that it puts the two aircraft in very close proximity, which is an exhausting task for a pilot and far too demanding for a normal autopilot system. But by combining a satellite navigation system with onboard measurements of the aircraft's movement, the AFF system could accurately maintain the wingman's position within 12 inches of the lead airplane.

The AFF research was conducted with two piloted F-18s to provide a secondary level of safety, since either pilot could take over and break away if the system wasn't performing as expected or required. The first round of flights took place between June 2000 and December 2001, and the system demonstrated drag reduction as high as 20 percent and fuel savings between 12 and 18 percent. Later flights, using an F-18 in trail behind a DC-8, showed fuel savings as high as 29 percent.

But in late 2001, the nation's priorities suddenly swung dramatically from fuel economy to homeland defense. That shift led to increased interest in unmanned aerial vehicles, since they were well suited for monitoring and surveillance missions. So instead of an initially planned third phase of flight tests with the AFF system, the autonomous formation flight experiments were redirected toward a new application – aerial refueling of UAVs.

UAVs

The Automated Aerial Refueling (AAR) research was a joint effort between NASA and DARPA. The AAR concept was geared toward UAVs, but the research flights were conducted using two of Dryden's F-18 research aircraft, for the same reason the AFF program chose to test the system with piloted aircraft. The F-18s were highly maneuverable aircraft with flexible systems that were well-suited to researching new avionics or integrated control systems, but having a pilot on board added an important layer of safety in flight testing a new and unproven automatic system.

The AAR program was a quick and inexpensive effort that was completed within a single year. One of the two F-18s used in the AFF program was converted into a tanker, and the second F-18 was hand-flown in formation behind the tanker to obtain data to model the aircraft/basket interaction—an important step in developing the automatic system software. The 23 flights in the AAR program encouraged DARPA to pursue the concept, and a second round of flight tests, in which the receiver F-18 would be flown automatically behind a Boeing Omega 707 tanker, began in 2006.

REMOVE BEFORE FLIGHT

Ground operations for the F/A-18 Autonomous Formation Flight project, November 14, 2001. (NASA photo EC01 349-10)

The impetus for shifting the AFF research to a UAV application may have been sparked by the increased interest in UAVs for surveillance and homeland security after the attacks on the World Trade Center and the Pentagon on September 11, 2001. But UAVs had been increasing in importance, both at Dryden and in the aeronautical world at large, throughout the 1990s.

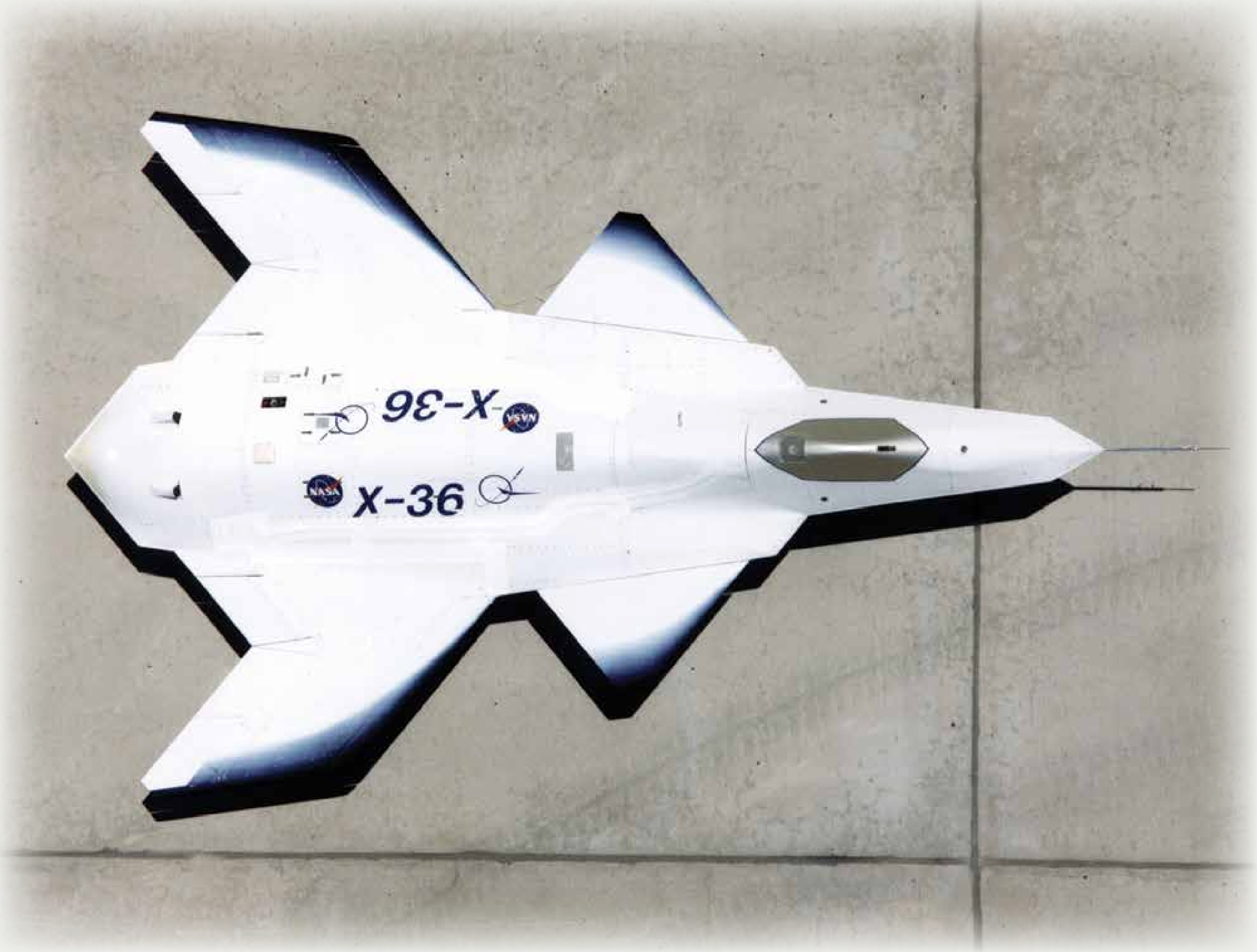
UAVs, or remotely piloted aircraft as they used to be called, had been used for aeronautical research since the 1960s. They were popular research platforms because they could be built more quickly and cheaply than a comparable piloted aircraft and do not need a life support system for the pilot. An unmanned test vehicle also allowed researchers to explore huge leaps in technology, because there was no human life at stake if a system or concept didn't work. In the 1990s, advances in materials, avionics, and computer technology combined to make UAVs practical for operational missions, as well – especially assignments that posed tremendous risk to a pilot or would be extremely tedious for a human to accomplish. Some have suggested that missions that are dull, dirty, and dangerous are ideal for UAVs. Dull missions are tedious to perform, dirty missions may involve flight through toxic environments, and dangerous missions may pose risks of damage or destruction to the vehicle. The military, in particular, was becoming keenly interested in UAV technology. As a result, Dryden found itself involved in an increasing number of UAV flight research projects between 1995 and 2006.

One such project, initiated by Ames Research Center and McDonnell Douglas in 1989, involved a tailless, thrust-vectored UAV called the X-36. Like the HiMAT research vehicle flown at Dryden in the 1970s and early 1980s, the goal of the X-36 was to explore how an unusual configuration and new technologies could improve aircraft maneuverability. In fact, some data from the HiMAT flight research program was used by the Ames/McDonnell team in designing the X-36.

While Dryden was not an original partner in the project, the X-36 team brought the two X-36 aircraft to the center for the flight research portion of the program to take advantage of the center's unique flight facilities and expertise in digital flight control systems. The tailless X-36 made its first flight in May 1996, and went on to complete an additional 30 flights over 25 weeks, during which the X-36 demonstrated agility superior to that of current fighter aircraft.

The X-36

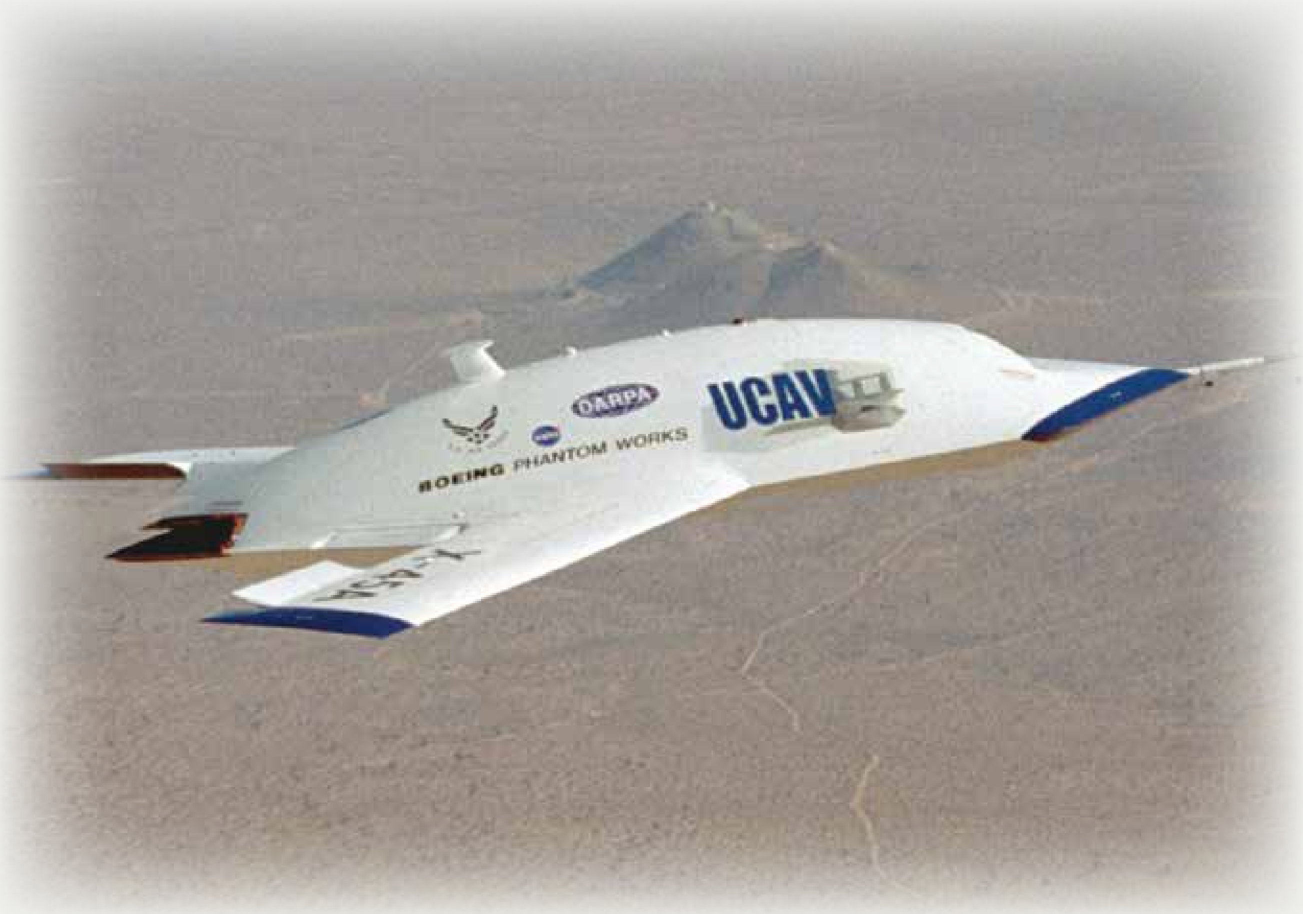
The X-36 was also a departure for Dryden in that the center's main role in the program was as a *"host"* center instead of having its engineers working as an integral part of a development and flight research team. The concept of *"hosting"* research efforts was a new one at Dryden, but it was a role the center was beginning to play more often, especially in the expanding world of UAVs. During the same year that the X-36 flew at Dryden, Boeing in a joint project with Lockheed Martin also brought a *"black"* UAV project called DarkStar to the center for flight-testing. As with the X-36, Dryden served primarily as a host of that project.



A McDonnel Douglas (later Boeing) X-36 seen from above on July 16, 1997. (NASA photo EC97 44165-151)

But the Dryden and Boeing engineers worked well together on both the X-36 and the DarkStar projects, leaving the Boeing team with positive feelings about Dryden as a flight research partner. As a result, when Boeing was awarded a subsequent DARPA/Air Force contract to develop a UAV that could demonstrate advanced UAV technologies, including weapons release from a *"stealthy"* UAV shape, and coordinated, common systems to allow UAVs to fly together and operate more efficiently with ground systems, Boeing again chose Dryden as its flight test partner.

Boeing's Unmanned Combat Air Vehicle (UCAV), also known as the X-45A, was a tailless UAV that weighed 15,000 pounds and measured 27 feet long, seven feet high, and 34 feet wide. Boeing built two of the experimental vehicles and the first flew at Edwards on May 22, 2002. In contrast to its pure host position with the X-36 and DarkStar host projects, Dryden also had an engineering role in the UCAV research. Since one of the objectives of the X-45A was to demonstrate the ability of combat UAVs to fly missions together, Boeing asked Dryden to work on anti-collision algorithms for the vehicles. Dryden was already working on autonomous anti-collision systems with the AFF/AAR programs, as well as for a separate anti-collision flight research effort with two F-16 aircraft, so the X-45A research fit in well with work the center was already pursuing. Dryden also developed autonomous taxi control laws for the UCAV vehicles.



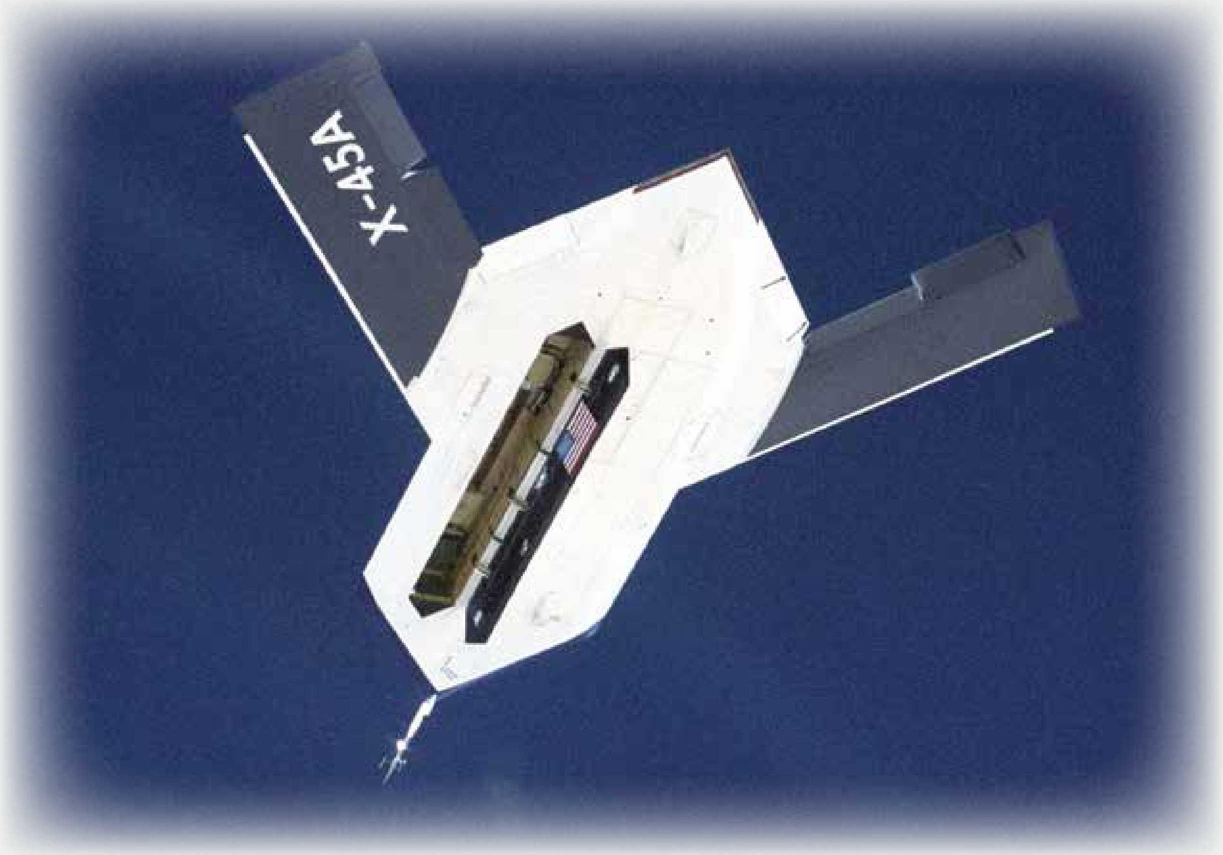
A Boeing X-45A Unmanned Combat Air Vehicle (UCAV) during a flight on December 19, 2002. (NASA photo EC02 0295-01)

The ERAST Program

The X-45A flights continued through 2003, and the technologies the vehicle was designed to demonstrate showed enough promise that DARPA and the Air Force initially decided to pursue a much larger and more operationally-designed version of the UCAV, although that program was subsequently cancelled.

The military was not the only entity interested in developing UAV technology in the late 1990s. The ERAST program that Dryden had begun in the early 1990s expanded throughout the second half of the decade as its participants developed UAV platforms and sensors to conduct high-altitude, long-endurance flights.

The ERAST program had two phases. In the first, all four companies involved in the Joint Sponsored Research Agreement (JSRA) – AeroVironment, Aurora Flight Sciences, General Atomics Aeronautical Systems (GA-ASI), and Scaled Composites – fielded different UAV designs with the help of NASA funding. In the second phase, AeroVironment and General Atomics received support to explore more capable follow-on designs. AeroVironment pursued a solar-powered variation on its original Pathfinder UAV design, while General Atomics developed a variation on its Predator UAV that used consumable fuels (as opposed to solar power, which is replenished automatically with each sunrise). Both follow-on efforts significantly advanced the state of solar-powered and consumable-fuel-powered UAVs, and General Atomics' work, in particular, ended up having a huge payoff for both the company and the U.S. military.



Another view of the X-45A with its weapon bay door open, February 21, 2003. (NASA photo EC03 0047-03)

When the ERAST program started, practical UAV technology was still in its infancy – a fact illustrated by the numerous mishaps that occurred with the early ERAST aircraft designs. But by the time the program concluded in 2003, both the technology and the market for that technology had advanced sufficiently that the burning question was not whether a UAV could be a practical aircraft, but how to incorporate fleets of them safely and efficiently into the national airspace system.

AeroVironment's Centurion unmanned aerial vehicle (UAV) in flight in November 1998, before it was modified to become the Helios UAV. 9NASA photo EC98 44798-01)

Alliance Partners

Not long after AeroVironment's initial Pathfinder aircraft set an altitude mark of just over 50,000 feet in 1995, the extremely lightweight aircraft was significantly damaged by a windstorm. The company rebuilt the Pathfinder with improved solar arrays, allowing it to reach 71,530 feet in July 1997 in the protected airspace of the Pacific Missile Range Facility off Kauai, Hawaii. While the aircraft was there, it also demonstrated some of its science monitoring capabilities by mapping reforestation on the island and nearby coral reef degradation using two instruments contributed by NASA Ames.

The following year, AeroVironment modified the Pathfinder with a center section from a larger solar-powered aircraft called the Centurion that AeroVironment was developing. The hybrid Pathfinder/Centurion aircraft was called the Pathfinder-Plus, and in 1998 it set yet another altitude mark of 80,201 feet and demonstrated three hours of sustained flight at 70,000 feet. Four years later, the Pathfinder-Plus was deployed to Kauai again to provide high-altitude imaging of the island's coffee fields as part of an effort to demonstrate the usefulness of solar-powered aircraft in mapping terrestrial resources.

The ERAST Program

The Pathfinder-Plus had better solar arrays than the original Pathfinder. But NASA had set two goals for the second phase of the ERAST program that even the Pathfinder-Plus was not equipped to meet. The first was an aircraft capable of reaching 100,000 feet. The second was an aircraft capable of sustaining flight above 50,000 feet for several days. AeroVironment's Centurion, which had a wingspan of more than 200 feet – twice the length of the original Pathfinder – was designed to reach that 50,000-foot altitude goal. The company also planned to build a separate aircraft to meet the program's endurance goal, which would require a more complex solar energy storage system.

The Centurion flew three times in 1998 using only battery power. But in late 1998, the ERAST program ran into funding difficulties. An option was developed that year to combine AeroVironment high-altitude and long-endurance designs into a single aircraft. The company agreed, and between the end of 1998 and mid-1999 modified the Centurion into the Helios Prototype aircraft. The Helios Prototype had a wingspan of 247 feet – longer, even, than a Boeing 747's – incorporating a sixth wing panel, a fifth landing gear pod, and solar panels that were 18 to 19 percent efficient. The original Pathfinder, by comparison, had a wingspan just under 100 feet, only two landing gear pods, and solar panels that were 14 percent efficient. And while the Helios Prototype still planned to use eight motors for long-duration flights, it was modified with 14 motors for high-altitude work.

The Helios Prototype flew for the first time in September 1999. Over the next year and a half, the company installed the aircraft's solar panels and made other modifications as subsequent flights illuminated deficiencies or problems in the design. Eight motors turned out to be marginal for the larger design, and the wingtips didn't stall or flex as predicted. The propellers twisted too much at high rpm and had to be redesigned, and a flaw was found in the aircraft's flight termination system (FTS). All UAVs must have an FTS so that, in the event of any loss of control, they can be brought to Earth under control and without harming anyone on the ground. The flaw in the Helios' FTS, therefore, had to be fixed before the aircraft could be cleared for flight.

In August 2001, however, everything came together, and the Helios took off from Kauai and soared to an altitude of 96,863 feet – two miles higher than any non-rocket airplane had ever officially flown. In addition, the aircraft stayed aloft for almost 17 hours – 40 minutes of which were above 96,000 feet. AeroVironment originally planned to modify the aircraft after that flight with a complex regenerative fuel cell system that might be able to keep the Helios Prototype aloft for months at a time. But the ERAST team concluded that the technology development required for the cells couldn't be accomplished before the end of the program in 2003. So AeroVironment installed a simpler hydrogen fuel cell system that, at least in theory, could keep the aircraft aloft for up to two weeks.

In the summer of 2003, the Helios team deployed again to Kauai to test the modified aircraft and the new fuel cells. The team got to 53,000 feet on one flight. But on a second flight a couple of weeks later the Helios hit unexpected turbulence in the air and began a pitching oscillation that kept increasing in amplitude. Soon the wings were bowing up and down to a shocking degree. Within a very short time, the amplitudes hit three times the aircraft's design limit, and it came apart, its pieces fluttering into the Pacific Ocean.

The Helios accident review board determined that the modifications made to the aircraft for its endurance flights, including the new fuel cell hardware, had made the vehicle more sensitive to atmospheric disturbances than its predecessors. But while the Helios program ended on an unfortunate note, the AeroVironment research with lightweight, solar-powered aircraft contributed significantly to the state of the art in both solar-cell technology and UAV design. In addition, the research demonstrated several practical applications for a slow-speed, high-altitude, solar-powered UAV that would almost assuredly lead to greater use of similar aircraft in the years to come.

The Aurora Flight Sciences Corporation, which built the Perseus proof of concept UAV in the early 1990s, developed and flew two other models in the ERAST program. The Perseus A used a closed-cycle engine to maintain air pressure at high altitudes. This was an experimental engine meant to operate in the stratosphere without a turbocharger, in this instance the closed-loop system mixed exhaust from the engine with fuel and fresh air before entering the engine. The Perseus B utilized a triple-stage turbocharger to keep its more conventional 80-hp Rotax® engine operating effectively in thinner air.

The ERAST Program

The Perseus B began flying in 1994, and it made two flights in 1996 before being damaged in a hard landing. Like AeroVironment, Aurora used the opportunity presented by having to repair its research aircraft to upgrade it, as well, and the improved Perseus B returned to Dryden in 1998, where it successfully reached an altitude of 60,280 feet. In October 1999, however, the Perseus B was severely damaged in an emergency landing. The aircraft's flight termination system was activated after a voltage spike wiped out its flight control actuators, but a misplaced cable prevented its FTS parachute from opening, leading to a landing near a freeway.

Aurora's third design of this type of aircraft, the Theseus, was a product of NASA Ames' Mission to Planet Earth science research program. The company began work on it in 1994 and brought it to Dryden for flight-testing in 1996, at the same time Aurora and Dryden were flying the Perseus B. The Theseus was powered by two 80-hp turbocharged piston engines, and the plane was designed to carry 700 pounds of instruments above 60,000 feet for more than 24 hours. Unfortunately, the Theseus went out of control on its sixth flight and broke apart, ending that particular research effort. Nonetheless, Aurora gained valuable experience and advanced the state of its aircraft design through its involvement with the ERAST program – experience the company was able to apply to subsequent commercial UAV endeavors. Flying UAVs was clearly more difficult than many expected, although this and other information was precisely what NASA's ERAST program was designed to draw out.

Even before the ERAST program began, General Atomics had developed and marketed a piston-powered UAV called the Predator A to the U.S. military, which had used the aircraft in the Kosovo conflict. But as part of the initial phase of the ERAST program, General Atomics developed a variant of the Predator A, called Altus, which was designed to fly at a higher altitude. General Atomics built two versions of the Altus. In 1996, the first Altus 1 reached an altitude of 37,000 feet and set an endurance record for a UAV, flying for more than 26 hours as part of a science mission. In 1997, the second Altus reached 43,500 feet, and the first Altus was brought back to the factory to be outfitted with a higher-capacity, two-stage turbocharger that enabled it to carry more instrumentation and reach a higher altitude. The modified *"Altus II"* began flights at Dryden in 1998. The following year, the Altus II proved itself capable of carrying 330 pounds of instrumentation to an altitude of 55,000 feet and remaining there for four hours. That same year, the Altus II also completed a series of successful high-altitude science mission flights, taking climate study measurements over the islands of Hawaii.

General Atomics Aeronautical Systems also had designs for a higher-altitude, longer-endurance, turboprop-powered UAV, but it didn't have a customer to justify the financial investment required to finish developing or building the aircraft. In 2000, however, NASA awarded General Atomics the contract for a follow-on vehicle to meet specific mission requirements for the second phase of the ERAST program – which gave GA enough external funding to justify the remaining in-house investment to build the aircraft. The contract called for GA to produce three prototypes of its new design: two non-research versions of the aircraft, which GA called the Predator B, and a third, upgraded version of the design, called the Altair. The Altair would be capable of sustained flight for 24-48 hours at an altitude of between 40,000 and 65,000 feet, carrying a payload of at least 660 pounds. The Altair was also designed to meet FAA requirements for UAVs operating in the national airspace system as well as on commercial UAV missions such as long-term monitoring of terrain, coastal areas, and forestry land.

General Atomics' bulbous-nosed Altair unmanned aerial vehicle during a flight on June 9, 2003. (NASA photo EC03 0154-03)

The ERAST Program

NASA's ERAST money and deadline pressure motivated GA to push ahead on the turboprop version of its Predator design, taking it from paper to flight in only 14 months. As a result, GA had both the Predator B and Altair prototypes available when the September 11, 2001 attacks occurred and the U.S. military began planning for action in Afghanistan. Suddenly, GA had a customer for its turboprop UAV – a customer so impatient, in fact, that the Predator B prototype was commandeered for the military's use. GA's original plan called for installing a single-string flight control computer (FCC) on its prototype Predator B aircraft and using the Altair to develop a triple-redundant FCC that could be integrated into production Predator B aircraft. But after 9/11, the Air Force took control of all three prototypes so that the triple-redundant FCC could be integrated more quickly into the operational Predator Bs. So NASA didn't get an Altair aircraft – which it leased from GA – until March 2004. Rarely does research lead to commercial application that quickly. But the timing in this case was just right. And if it had not been for the ERAST program, General Atomics would not have had the Predator B available when the country needed that kind of aircraft.

PROTEUS
N281PR

Resembling a giant mosquito, the Proteus aircraft flies above the mountains near Las Cruces, New Mexico, on March 15, 2002. (NASA photo EC02 0057-53)

Burt Rutan's Scaled Composites, Inc. contributed two unusual aircraft to the ERAST program, both designed to be flown either remotely or by an onboard pilot. The first aircraft, the *“Demonstrator ^{2},”* was powered by a 100-hp Rotax® engine and used primarily to test the design's ability to communicate with the Tracking and Data Relay Satellite System (TDRSS).

Scaled Composites' second aircraft, called the Proteus, was a larger, insect-shaped, jet-powered vehicle designed for multiple applications ranging from atmospheric research to commercial imaging, telecommunications relay services, and satellite launching. But its larger size and thrust made it capable of carrying a far larger payload – up to 2,000 pounds – to altitudes above 60,000 feet and sustaining that altitude for up to 14 hours. Its capabilities as an optionally piloted vehicle also made it an ideal platform with which to research automatic flight control systems. In 2003, it conducted a series of flights to research collision-avoidance-system technology, which would be a critical component to the practical operation of UAVs in the national airspace system.

ARENA ARCTICA
NASA
809
DRYDEN

ER-2 #809 undergoing pre-flight fueling in Kiruna, Sweden for a research flight mission in the Arctic, January 24, 2000. (NASA photo EC00 0037-03)

Airborne Science

While one of the primary applications of the ERAST aircraft was, clearly, environmental research, the ERAST program was focused on the development of the aircraft themselves and related technologies such as sensors, flight termination systems, and collision-avoidance software. Dryden, after all, had always been in the business of furthering aerospace technology and vehicles, not in performing operational missions with those aircraft or spacecraft after the technology was in place.

But in 1997, NASA consolidated more of its aircraft and flying missions at Dryden, so the center inherited three Airborne Science aircraft that, until that time, had been operated by the Ames Research Center. The aircraft consisted of two high-altitude ER-2s (a variant of the U-2 spyplane made famous when Francis Gary Powers was shot down over the Soviet Union in 1960) and one DC-8 transport aircraft. The DC-8, which had been converted to science use in the mid-1980s, was an unusual airborne laboratory that could support 40 scientists conducting 14 different experiments simultaneously. The ER-2s, on the other hand, could fly high enough to be above 95 percent of Earth's atmosphere, which gave the ER-2s another valuable and unique niche in collecting science data.

From 1998 to 2005, the ER-2s and the DC-8 were deployed around the world for a wide variety of science missions. They gathered data on hurricanes, coastal eddies, terrain changes, arctic ice formations, wildfire damage, pollution and airborne particulate matter, cloud characteristics and influences, atmospheric and soil moisture, and topographical disturbances or changes. The aircraft were also used to calibrate satellite instruments and data, as well as for sensor development and testing. The DC-8, in particular, was very active in developing and testing an airborne radar imaging system for Earth science experiments, known as the Airborne Synthetic Aperture Radar, or AirSAR. AirSAR has the capability to acquire extremely accurate topographic information that is a key ingredient in many Earth science programs.

The ER-2s and the DC-8 became the primary aircraft at Dryden used for science missions, although the center also used a Gulfstream III for some projects. In 2002, Dryden also enlisted one of its F-18s to fly a digital imaging system up to 49,000 feet to allow scientists to look for asteroids near the sun without so much interference from the Earth's atmosphere. But even as Dryden expanded its work into airborne science missions, there remained some question within NASA about whether the agency should be operating proven aircraft designs, especially as budgets declined and pressure increased to transfer more of NASA's less-risky functions to private industry or other entities. So in 2005, the DC-8 was transferred to the University of North Dakota.

Some at Dryden questioned whether an academic institution, even one with a strong aeronautics program, could effectively maintain and operate a large, four-engine, jet transport equipped with complex scientific instrumentation on a regular schedule of research missions. It is a legitimate question that speaks to a fundamental issue with regard to NASA's role in the aerospace world. Clearly, Dryden has accumulated a remarkable level of expertise in flight research over the past 60 years, allowing the center to have a very high success rate in terms of both safety and mission success. More diverse institutions or companies generally don't have that level of focus or experience. But it costs money to have NASA operate testbed and research aircraft – money that other companies and institutions often argue they could put to more efficient use.

What amount of research or budgetary dollars, and what tasks, should be allocated to NASA facilities versus outside research or commercial entities? The answer, and the right balance, is tricky to get right. Opinions on the matter are also often at least partly influenced by which side of the fence a person sits on, or which philosophy of governmental versus private enterprise roles a person or management team embraces. But it's a question that NASA has struggled with, especially in the field of aeronautics, for a long time. And it's an issue that will almost surely continue to be debated as long as the world keeps changing, technology and industry keep progressing, and NASA endures.

Philosophy wasn't the only reason the DC-8 was transferred to UND, however. There was also the very real fact that the airplane was expensive to operate and, as Dryden entered the 21st century, the center was under real budget pressures that were affecting not only its atmospheric research aircraft, but testbed aircraft and research facilities, as well.

The DC-8 taking off from Kiruna, Sweden, in January 2000 during the SAGE III Ozone Loss and Validation Experiment (SOLVE). (NASA photo EC00 0037-08)

Testbeds & Research Facilities

Since its earliest days, Dryden had maintained a variety of both ground and flight research facilities. The center's Flight Loads Laboratory (which has gone by several names in its history) was built in 1965 to conduct combined mechanical and thermal load tests on both structural components and complete flight vehicles. That facility, which is still used by NASA, industry, and other government researchers, has compiled an enormous database of critical information on aerodynamic and thermal forces that act on aircraft in flight. Dryden's simulation facilities, including its hardware-in-the-loop capability housed in the center's Walter C. Williams Research Aircraft Integration Facility, have provided pilots and engineering researchers with invaluable information on systems and components before taking concepts to flight.

The aircraft flown at Dryden were generally more visible than the ground facilities, but to Dryden researchers, the aircraft were also considered research tools that could be used to gather data and demonstrate the viability or capabilities of concepts or technology. Indeed, even aircraft like the X-15 or F-8 Digital Fly-By-Wire, which were initially built or modified for a specific research program, were used for follow-on or *"piggy-back"* experiments after their primary research goals were met. And while the center's NB-52B was not originally envisioned as a testbed aircraft, it ended up providing launch and research services to an incredibly wide variety of project teams over its 45 years of service at Dryden.

SRA
845
SYSTEMS RESEARCH AIRCRAFT

The F-18B Systems Research Aircraft (SRA) on July 28, 1998. (NASA photo EC98 44672-01)

NASA
30502
UNITED STATES OF AMERICA

A Gulfstream III (C-20A) aircraft flying low on April 18, 2003. (NASA photo EC03 100-1)

As computerized systems, components, and advanced materials began to play an increasingly important role in aircraft design, however, Dryden strengthened its support and use of testbed aircraft whose main function was conducting experiments on aircraft components or systems. In addition to its F-18 Systems Research Aircraft (SRA) testbed, which conducted a variety of flight experiments throughout much of Dryden's sixth decade, Dryden also acquired an F-15B from the Hawaii Air National Guard in 1993, and that aircraft became another workhorse for smaller projects and experiments. While not a fly-by-wire aircraft, the F-15B did have a specialized data-acquisition system and two special test fixtures that could be attached on the underbelly of the aircraft. The first Flight Test Fixture (FTF) allowed the aircraft to serve as a supersonic wind tunnel for laminar flow, materials, structures, and other aerodynamic experiments. A second, the Propulsion Flight Test Fixture (PFTF) developed for the F-15B in 1999 allowed small propulsion-related experiments to be flight tested expeditiously and cost-effectively.

The center also acquired a King Air (in 1997) and a Gulfstream III (in 2003) that have been used for developing and testing research instrumentation, sensors, and avionics. And while Dryden's original NB-52B aircraft, which had launched the X-15, the lifting bodies, the X-43, and innumerable other flight research vehicles, was finally retired in 2004, it was replaced for a while with a B-52H launch aircraft to preserve the center's vehicle launch capabilities, until operating costs sent it, too, into flyable storage.

The advantage of Dryden's testbed aircraft is that they allow numerous experiments in component or systems research to be tested in flight for a reasonable cost. Indeed, many of the projects flown on Dryden's testbed aircraft would not have flown if the projects had required funding for a dedicated research aircraft. Given the importance and benefits of testing aeronautical concepts in a real-world environment, the value of flexible testbed aircraft seems clear. The problem is, again, a budgetary one. It costs money to maintain a research testbed, just as it costs money to maintain a national research laboratory or wind tunnel. So managers have to balance the benefits of having testbed aircraft like the F-15B or B-52H against the costs of maintaining and operating them.

This problem became more acute in late 2003, when NASA instituted full-cost into its program management budgets. Until that time, NASA's employees and facilities were institutionally funded, so individual research projects were budgeted based on whatever additional manufacturing, flight, or contractor costs the research would incur. Under full-cost, budgets were adjusted to include the costs of facilities and employees. Full-cost can be implemented simply as a way of getting more information on the actual costs of doing business, in which case the system doesn't directly affect funding of any particular project. But the way full-cost was implemented at NASA was closer to the concept of full-cost recovery.

The way full-cost was implemented at NASA, the cost of maintaining facilities and employees was not simply tracked on paper. Those costs were also suddenly billed out to clients and paid out of project budgets. Without institutional funding, the only way to maintain flying testbeds was to have the aircraft in almost constant use. Dryden suddenly found itself scrambling for customers to use its testbeds and putting some of the aircraft into flyable storage when enough customers couldn't be found. Unfortunately, full-cost also meant that at the same time, Dryden had to begin passing on significantly higher costs to research partners who wanted to fly experiments on the testbeds, which made it more difficult to find enough customers to keep those aircraft flying.

In addition, in a stroke of particularly unfortunate timing, these changes came just as Dryden was facing cuts in its funding from NASA Headquarters. The center had geared up to compensate for those cuts by more aggressively seeking out good research partners who could contribute money to projects and augment the center's NASA funding. But with full-cost, the center suddenly became a more expensive research partner. It was a difficult challenge. But then, Dryden has never had a time where challenge wasn't part of the equation, whether it was flying an X-15, working with increasingly complex project teams and structures, adjusting to changing priorities and funding, or constantly working at the uncertain edge of knowledge and capability with careers and lives on the line. Dryden was simply entering yet another chapter in the book of change that guided the center forward ever since the X-1 took to the skies.

NASA research pilots Frank Batteas (back to camera), Gordon Fullerton, left, and Ken Wilson during a pre-flight briefing for the B-52H, February 5, 2004. (NASA photo EC04 040-03)

Conclusion

In some ways, Dryden's work in its sixth decade contained the same elements and challenges that had characterized the center in previous years: a wide variety of research projects, a multitude of different partnership agreements, and constant adaptation to changes in technology, national priorities, and internal organization. And, as in previous eras, the center's efforts contributed to a significant number of technological advances in both atmospheric and space flight.

Between 1995 and 2005, Dryden's portfolio included research in space vehicles, launch systems, and engines; supersonic and hypersonic flight; high-altitude, subsonic flight; highly integrated aircraft flight and engine control systems; more efficient aerodynamic configurations; UAV designs, sensors, and systems; environmental research platforms and missions; and new propulsion concepts. In addition, the center's testbed aircraft supported numerous experiments to gather data and conduct research on materials, components, and technology ranging from a space-based telemetry system to potentially dangerous foam divots on the shuttle's external fuel tank.

At the same time, however, there were some fundamental changes in both organization and the type of research projects and aircraft at the center. In previous decades, Dryden had rarely served as a host for an outside research effort. In part, that arrangement was due to the fact that NASA was providing at least some of the funding for those efforts. But Dryden's typical approach to project management, which historically involved a greater role for the center's researchers in both engineering and flight safety, also sprang from the center's convictions about what elements were important to integrate a successful flight research effort with a high degree of flight safety.

With the advent of UAVs, however, an argument could be made that there might not be a need for such strict guidelines, as long as the vehicles had a reliable flight termination system. Mission success was still at risk, of course, but the stakes were inarguably lower than with a piloted aircraft. Many of Dryden's industry partners also had more flight-test experience and knowledge than they'd had a half-century earlier. As a result of all these converging forces, Dryden's management began to show more flexibility in the level of involvement the center would, could, or should play in different research projects – especially as the center's need to attract external projects and customers increased. Nonetheless, Dryden realized that the center's needs did not absolve NASA from ultimate safety responsibilities, especially with UAVs.

The aircraft at Dryden were changing, as well. The big-iron, high-performance rocket planes were starting to be replaced, at least for some missions, by increasingly capable UAVs. While this development wasn't popular with the pilot office, the truth was that advances in computing and aircraft system technology were beginning to give UAVs some of the same capabilities that, at one time, only piloted fighter aircraft could offer. The challenges and possibilities of new flight control laws, integrated aircraft systems, and aerodynamic design were still there, of course – and in some cases were more intriguing than ever. But the flight line was undeniably changing.

In addition, the pace of change was accelerating. Dryden's researchers were accustomed to – even excited by – developments in technology. But the changes in organizational direction, funding, and priorities were more difficult for them to absorb. Indeed, some real threats loomed on the horizon: the possibility of not being able to maintain national research facilities or functions, the risk of losing the center's invaluable project and institutional knowledge with more frequent project and staff changes, and the danger of losing the incredible enthusiasm that had always characterized the staff at the Dryden Flight Research Center.

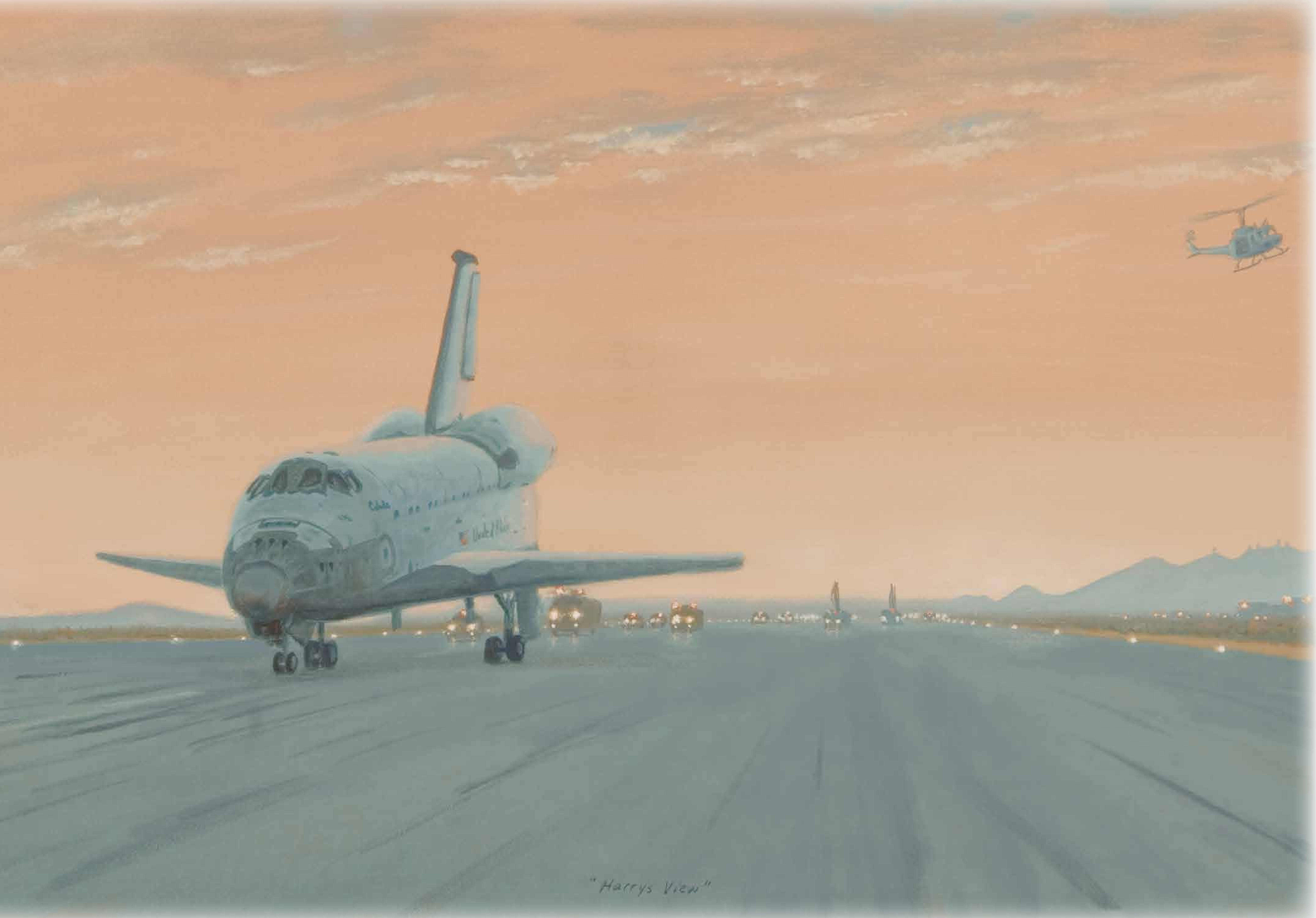
But at the same time, those threats offered Dryden some potential long-term benefits. The changes in funding, structure, and project management were forcing Dryden to become even more flexible, which is always helpful for an institution's long-term survival. But these developments were also forcing Dryden to get more aggressive in pursuing innovative research partnerships outside of NASA. In the long run, that search is going to make the center more useful and relevant to industry and the nation, improve its fiscal condition, and leave it less vulnerable to the shifting political winds off the Potomac.

1 Dave Lux, interview with author, July 15, 2005, Edwards, Ca.

2 Joe Pahle, interview with author, June 24, 2005, Edwards, Ca.

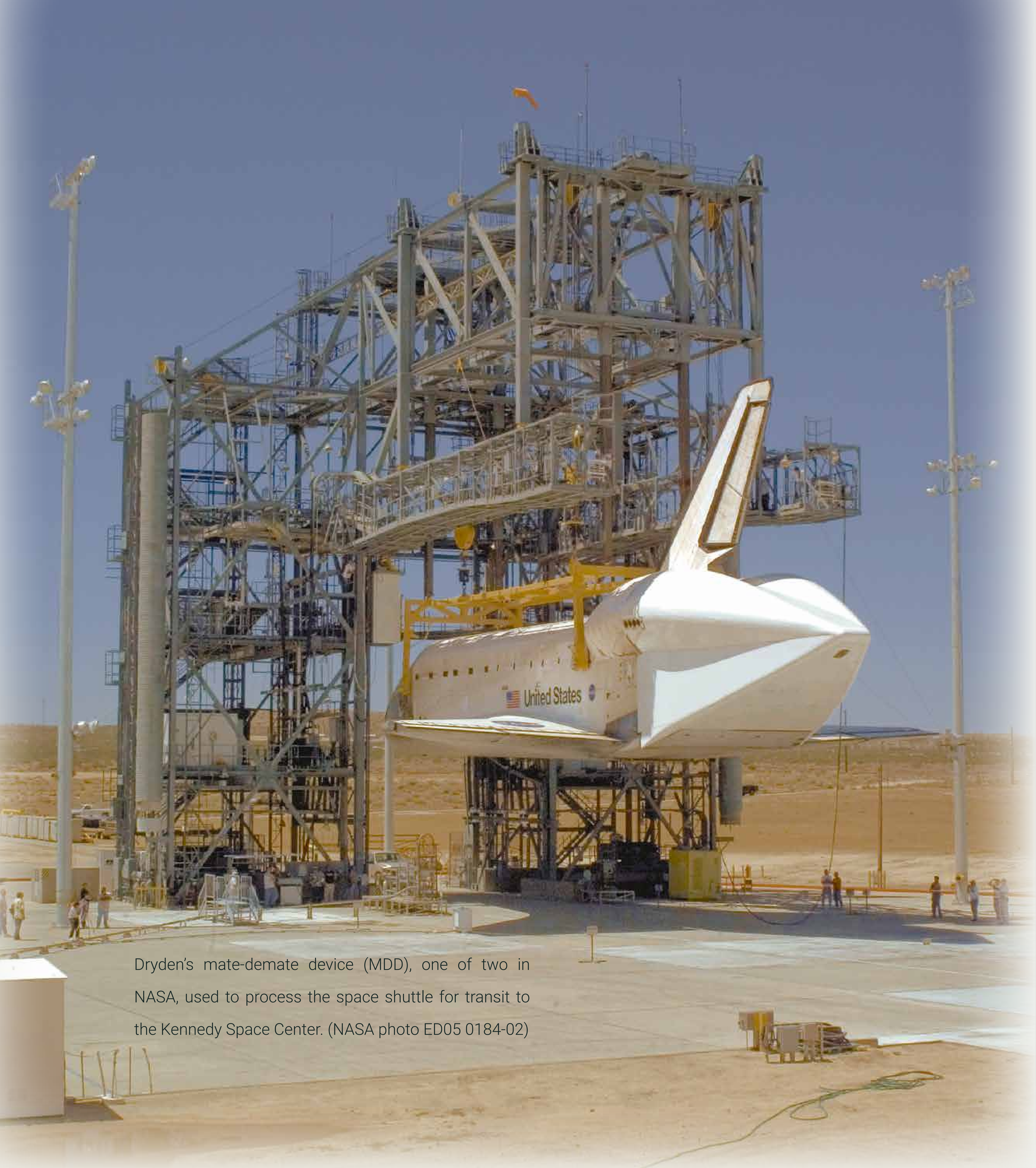
Chapter 8

New Horizons


"Harrys View"

Harry's View

by Mark Pestana



Dryden's mate-demate device (MDD), one of two in NASA, used to process the space shuttle for transit to the Kennedy Space Center. (NASA photo ED05 0184-02)

New Horizons

While it is true that the only constant at Dryden has seemed to be change itself, not all the changes have been the same order of magnitude. The center's programs and organizational structures have always been fluid. But there have also been several times in Dryden's history when more fundamental elements of the center's existence or mission were either questioned or altered. There was serious discussion on Capitol Hill about closing Dryden completely, as some legislators believed that *"no future activity beyond the X-15 would require the existence of the Center."*[1] Clearly, Dryden and history proved them wrong. But in 1981, policy changes at NASA Headquarters resulted in Dryden losing its status as an independent NASA research center. For the next 13 years, Dryden operated as an adjunct facility to NASA's Ames Research Center.

The changes Dryden faced as it approached its 60th anniversary were not as severe as those earlier challenges to its basic existence, status, and day-to-day operations had been. But they were also far more significant than a mere shuffling of specific research projects or priorities. And then, at the beginning of 2004, the entire National Aeronautics and Space Administration altered its research direction and focus – a shift that affected not only Dryden, but every NASA center and program.

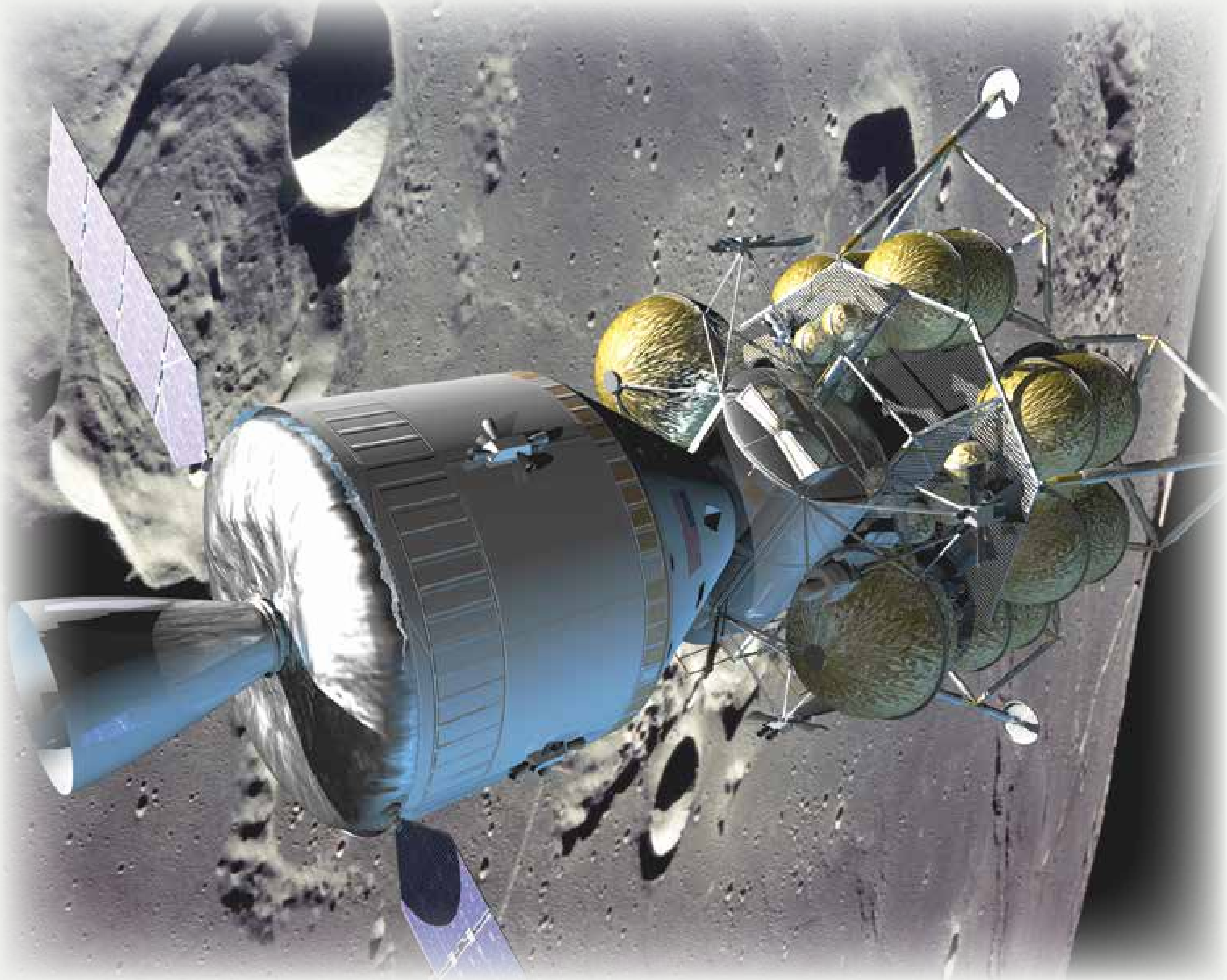
On January 14, 2004, President George W. Bush announced a new vision for America's civil space program that included sending human astronauts back to the moon and then on to Mars. It was a dramatic departure from the focus on Low Earth Orbit (LEO) missions that had dominated NASA's thinking about follow-on vehicles for the shuttle since the early 1990s. The science arm of NASA had been working on robotic and other astronomical explorations beyond the Earth's orbit for more than 40 years. But to send astronauts on more distant missions – and to contemplate a crewed mission to Mars – was a tremendous undertaking and challenge.

Developing the necessary components, systems, vehicles, and support structure for such an ambitious undertaking was also going to require a serious research investment, and NASA's budget was not slated to increase significantly. So to make the president's vision possible, NASA was going to have to change its research budget and agenda significantly. In some ways, the shift was no different from many other policy or priority alterations the agency had made over the years. Nevertheless, realigning the agency to support such an expansive, long-term effort was going to have a larger impact than some of the other changes that NASA, and Dryden, had endured in the past.

Crew Exploration Vehicles

The year after President Bush laid out his space exploration vision, a new leader also took the helm at NASA. Michael Griffin, who held a doctorate in aerospace engineering and had once served as NASA's chief engineer, faced the difficult task of making the necessary organizational, project, and budget changes to support the new exploration agenda. He also had some ideas of his own about how to improve the NASA administrative organization. As a result, Dryden soon faced some abrupt changes in its research and funding.

Traditionally, NASA centers had been organized into, and received the bulk of their funding from, different directorates at NASA headquarters. Dryden, Langley, Ames, and Glenn fell under aeronautics. Johnson, Marshall, Stennis, and Kennedy came under space flight. Goddard and the Jet Propulsion Laboratory were affiliated with science. Griffin, however, realigned all the centers to report directly to his office, to allocate more of the agency's work to the centers. That decision, in addition to the already declining NASA budget for aeronautics and the increasing financial demands of the agency's new exploration mission, affected Dryden in several ways.



The Crew Exploration Vehicle NASA envisioned in 2006 and meant to carry astronauts to the Moon and Mars. (NASA/John Frassanito and Associates image)

The first impact was a greater decrease in funding, or outright cancellation, of several aeronautics research efforts Dryden had been planning. NASA simply didn't have the money to continue doing everything it had been doing and still take on an ambitious new space exploration program. Follow-on research planned for high-altitude, long-endurance unmanned aerial vehicles was eliminated, as was funding for *"flight demonstrators,"* better known as *"X-planes."* In addition, the center's fleet of F-18s would most likely be reduced, and its B-52H *"mothership"* would probably have to be given back to the Air Force.

On the other hand, Dryden suddenly found itself with a larger role in developing the Crew Exploration Vehicle (CEV) for the new space program. The center was also given approval for conducting a greater number of operational science missions with its piloted and remotely piloted aircraft. So while Dryden's support from the aeronautics wing of NASA was declining, its funding from the Science and Space Exploration Mission Directorates was actually increasing. In addition, Griffin proposed increasing the institutional funding support for the center, so Dryden, as well as, other centers would no longer have to incorporate its entire overhead into the cost of each project. Instead, NASA would provide institutional support for Dryden's indirect operating costs, such as accounting, physical plant maintenance, and administrative personnel. Consequently, Dryden would only have to charge its research partners and customers for the direct costs of research projects, which would make the cost of conducting research at Dryden more affordable for potential partners.

And while there was less money for building aircraft or hardware, there was still some support available for aeronautical research at Dryden. Griffin also wanted the center to keep pursuing cooperative partnerships for aeronautical research, in addition to seeking out fully reimbursable research projects with external customers. The only difference was that NASA's contribution to those partnerships might now be the people, instead of dollars. Griffin felt strongly about keeping NASA personnel involved in hands-on research projects because he wanted to both hone and maintain the agency's in-house expertise in aeronautics and space flight. The vision for space exploration that President Bush had outlined would involve a long-term commitment, and Griffin wanted to ensure that NASA retained the in-house knowledge, experience, and savvy to manage the program well and provide continuity to the effort from year to year, and decade to decade.

Space Exploration

The combined impact of all of these changes – from a new approach to project budgeting and reductions in the aeronautics budget, to a complete realignment of the NASA centers and their funding sources and the advent of a completely new and overshadowing space exploration effort – amounted to something more like a tidal wave than a mere sea change. Fortunately, Dryden was not facing the wave unprepared.

For one thing, Dryden had been practicing flexibility, and enduring shifts in its research funding and projects, ever since the center was formed. Some forward-looking Dryden managers had also anticipated the decline in aeronautics funding from Headquarters as early as 2003. So by the time the agency switched to full-cost and announced the new space exploration initiative, the center had already begun changing its organizational structure and emphasis to attract a client and funding base beyond NASA.

In addition, Dryden had supported NASA's space research efforts since the Mercury program. Perhaps even more important, helping to develop a CEV isn't all that different, at the core, from developing or testing X-43As, Lunar Landing Research Vehicles, or any other research vehicle. Because, as one of Dryden's project managers noted, *"the principles that govern these projects are the same. We still have checkout of a vehicle and its systems, configuration management, risk management ... all the things we do to fly aircraft and keep them safe."*[2]

The world had changed. NASA's priorities had shifted. The test vehicles and projects were different. But Dryden was still doing what the center had always done best: putting concepts and hardware together into real systems and taking those systems to flight. And whether those systems were designed to improve engine designs, gather data on new aircraft configurations, improve aircraft efficiency or safety, expand our understanding of the atmosphere, or return astronauts to Earth again safely in an emergency, the importance of Dryden's role was unchanged. For flight was still the only way to gather actual, incontrovertible, real-world data on a wide range of scientific or atmospheric phenomena, aircraft configurations, or even spacecraft system designs.

Space Exploration

NASA had known since the early 1990s that the aging shuttle fleet would have to be replaced eventually. But until January 2004, NASA had focused its efforts on reusable, lifting-reentry launch vehicles, including lifting body designs, to service Low Earth Orbit (LEO) missions. If the goal was distant space flight, however, a lifting reentry vehicle made less sense than a basic capsule shape, like that used in the Apollo program. So after President Bush's speech, NASA's design focus shifted dramatically away from hypersonic, winged, or lifting body shapes in favor of an Apollo-type crew capsule. Of course, technology – in terms of materials, computing power, systems and even guidance – had advanced by great leaps since the last capsules were designed. So the new Crew Exploration Vehicle would resemble the old Apollo vehicles in exterior appearance only.

Hyper-X
DRYDEN FLIGHT RESEARCH CENTER
NASA

NASA's venerable NB-52B mothership cruising to a test range over the Pacific Ocean with the third X-43A hypersonic research aircraft attached to a Pegasus® rocket for a flight to nearly Mach 10 on November 16, 2004—a mission that helped prepare Dryden for its work on the Crew Exploration Vehicle. (NASA photo EC04-0325-23)

But, like the Apollo capsules, the new CEV would need to have some kind of launch abort system to allow the astronauts to return safely to Earth in case of a mishap on the launch pad or during the vehicle's initial rocket-powered ascent. In the Apollo program, the launch abort system was tested with the help of General Dynamics/ Convair *"Little Joe II"* solid-propellant rockets, which launched boilerplate Apollo capsules, built by North American Aviation, from the White Sands Missile Range in New Mexico. The new CEV would need a similar testing program.

The CEV development program is based at the Johnson Space Center. And while the CEV shape differed greatly from the CRV that JSC had worked on with Dryden in the 1990s, many of the CEV program personnel were veterans of the X-38 research project. And they knew how valuable Dryden's experience in flight-testing and controls had been to that effort. So the Johnson crew recruited Dryden once again to help them develop and execute a test program to human-rate the CEV launch abort system at various stages of launch and flight.

Some of the other space-related concepts that Dryden had been exploring, such as the Mars Aero-Assist Transfer Vehicle, had to be put on the shelf temporarily to focus resources on getting the basic CEV developed and operational. But innovative new vehicles and systems for accessing the atmospheres and surfaces of other planetary bodies were almost certainly going to play an important role in NASA's future, if the nation wanted to continue its efforts to explore beyond the confines of planet Earth.

Airborne Science

While the new space exploration initiative certainly commanded a significant portion of NASA's focus after January 2004, work continued in both science and aeronautics. Indeed, Dryden's commitment to science was, if anything, increasing. Dryden had begun conducting airborne science missions in the mid-1990s, due to both the center's involvement in the UAV-based ERAST program and the decision of NASA Headquarters to move three science platform aircraft – two ER-2s and a DC-8 – from Ames to Dryden in 1997. The ERAST program concluded in 2003, but in 2004, Dryden started using the General Atomics Altair UAV, which the company had developed as part of the ERAST program. Initially, Dryden leased the high-altitude Altair for further sensor and systems research, as well as for operational data-gathering science missions. But in 2006, Dryden also purchased one of General Atomics' production Predator B aircraft for UAV research and science missions.

NASA's DC-8 science-platform aircraft in March 2004 during an expedition to Central and South America to use an Airborne Synthetic Aperture Radar for a variety of scientific applications. (NASA photo ED04-0056-117)

An unusual photo of pre-Columbian archaeological ruins taken in the Costa Rican rain forest during NASA's AirSAR 2004 Mesoamerica campaign with the DC-8 airborne laboratory. (NASA photo ED04-0056-050)

The fact that Dryden could purchase a production-model UAV for operational science missions actually spoke volumes about the success of the ERAST program, and how far UAV technology – and the UAV industry – had come in only a decade. UAVs had evolved into reliable vehicles that could be evaluated, along with other aircraft, as potential research platforms.

In 2005, Dryden teamed up with the National Oceanic and Atmospheric Administration (NOAA) to evaluate the ability of UAVs like the Altair to conduct remote science missions related to oceanic, atmospheric and climate research, nautical charting, and coastal fisheries and sanctuary assessment/enforcement. Other planned missions with the Altair and Predator B included work for the Coast Guard, other NASA research centers, and wildfire monitoring experiments with the National Forest Service.

NASA ER-2 and DC-8 aircraft in a hangar in Kiruna, Sweden, during a project to study ozone depletion above the Arctic Circle in 2000. (NASA photo EC00-0037-1)

General Atomics' Altair unmanned aerial vehicle flying a mission in cooperation with the NOAA to do coastal mapping, marine monitoring, and mammal observation off the California coast on November 16, 2005. (NASA photo ED05-0234-28)

The policy shift regarding Dryden's involvement in operational science missions also gave the center's ER-2s a new lease on life, at least in a moderate capacity. The decision also made sense from a sheer logistical standpoint. Few non-governmental science laboratories had the facilities, resources, personnel, or equipment to operate high-performance, high-altitude aircraft, but the ER-2s could still perform unique and important missions. They could take readings and drop sounding equipment from above weather systems or hurricanes – or above most of Earth's atmosphere, for that matter, and they can carry far greater payloads than current UAVs. And the relative cost of maintaining and operating the aircraft was lower for Dryden, with its vast experience in high-altitude flight and stable of high-performance aircraft, than it would be for most other facilities.

Dryden's expertise in flight research operations also prompted NASA to move the SOFIA airborne telescope project to Dryden in 2006. The SOFIA project – for Stratospheric Observatory for Infrared Astronomy – was a joint U.S. and German effort to build and operate a 2.5-meter infrared telescope mounted inside a Boeing 747SP. Mounting a telescope in a jet transport aircraft allowed researchers to capture images from altitudes high enough to be above much of the distorting atmosphere and above 99 percent of Earth's water vapor. In fact, the SOFIA was designed to replace the very successful .91-meter Kuiper Airborne Observatory, which had flown aboard an Ames Research Center C-141 for 20 years.

NASA's SOFIA Boeing 747SP is readied for an extensive flight test program to ensure the airborne telescope will function at its best. (NASA photo ED06 0192-01)

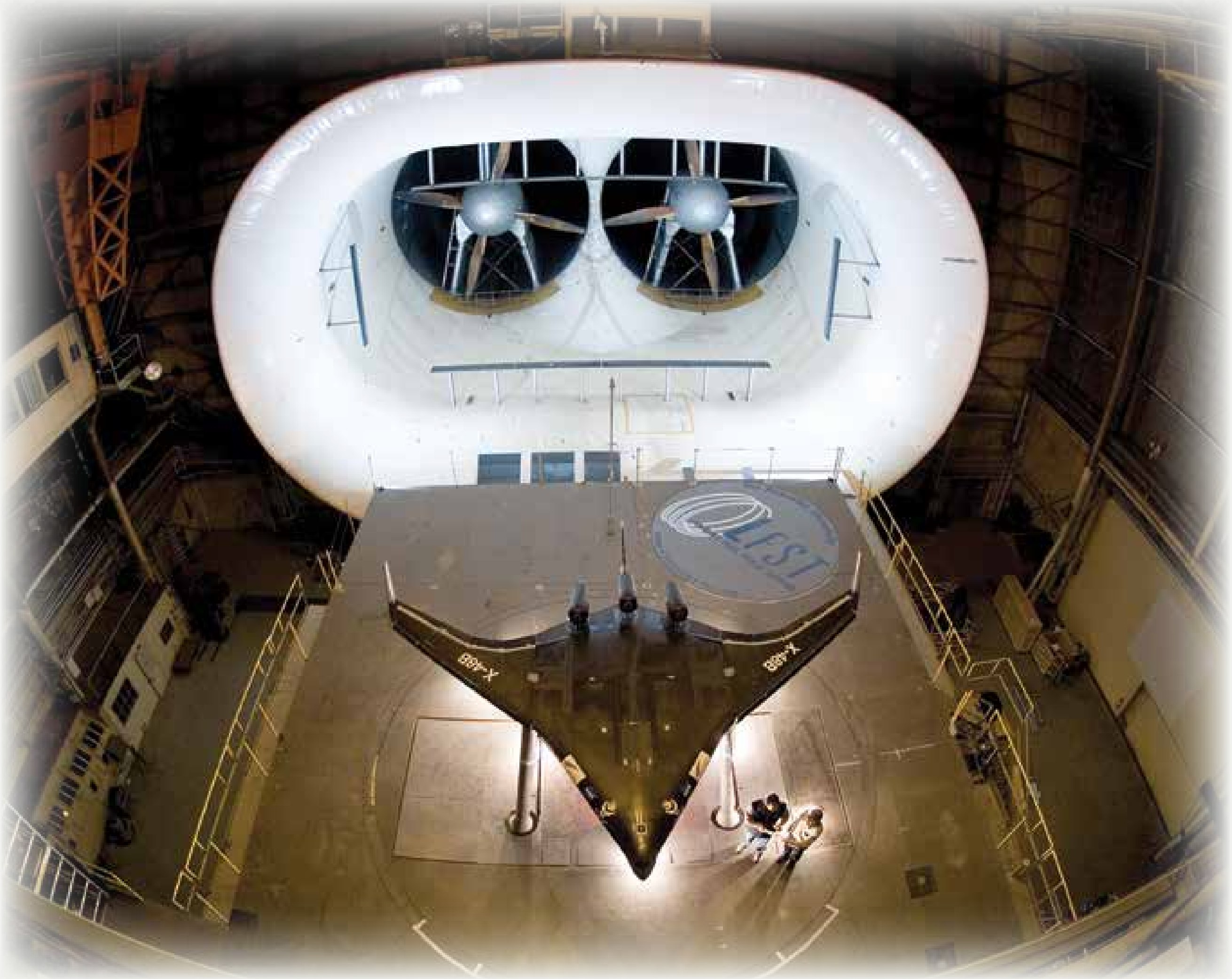
The SOFIA development program began in 1996 and was initially slated to fly in 2001. But the program ran into problems and delays and, in February 2006, NASA withdrew funding for the program. But the project was so close to completion, and had such potential scientific value that the agency subsequently decided to continue the program but to bring Dryden in to manage the final system integration and flight evaluation of the science platform.

Aeronautical Research

While Dryden's aeronautical research budget from NASA declined, the center was still involved in numerous aeronautical research projects. Some of those projects were funded internally, while others were joint partnerships with external industry or other government partners.

The blended wing body concept, for example, which had been shelved several years earlier, suddenly reappeared on Dryden's flight schedule. Boeing, Langley, and the Air Force Research Laboratory (AFRL) had developed two remotely piloted scale models of a blended wing body design that the Air Force had designated the X-48B. In theory, a blended wing body design could allow an aircraft far greater cargo capacity without the need for impractically long wings. By the spring of 2006, the X-48B team was testing the two 21-foot-wingspan models in Langley's wind tunnels, and flight research with the vehicles was scheduled for Dryden later in the year.

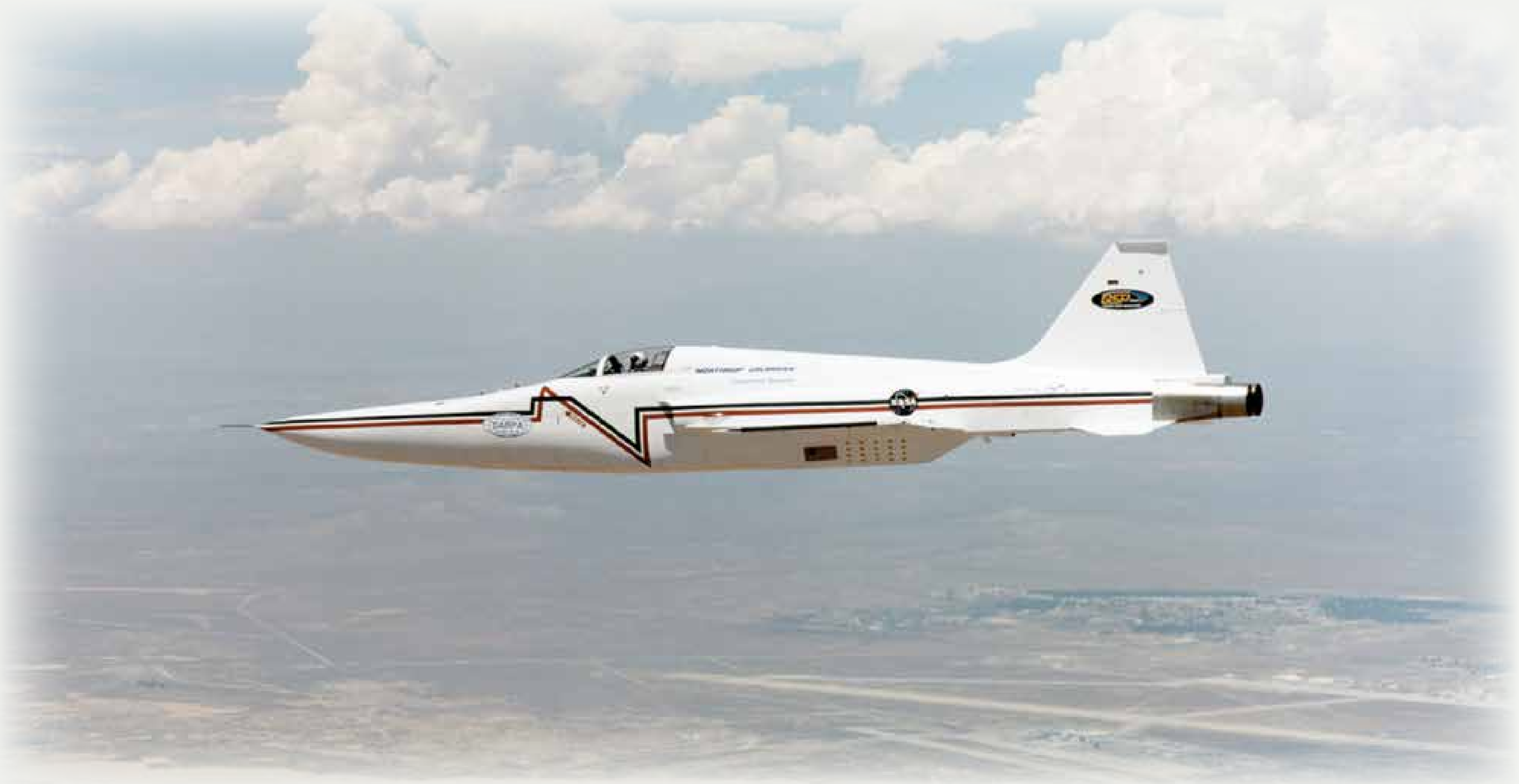
The *"morphing"* aircraft concept also saw a resurgence as Dryden entered its seventh decade. DARPA and the AFRL initiated a morphing aircraft structures program, focused on technologies that would allow a wing to change shape in flight in order to give an aircraft greater mission flexibility. In a sense, the morphing aircraft program was an evolutionary step beyond the Active Aeroelastic Wing, which was also a DARPA/Air Force project. The morphing aircraft structures team planned to explore some possible morphing technologies and concepts on a small, remotely piloted vehicle, and at least part of the flight research with that vehicle would very likely take place at Dryden.



The X-48B Blended Wing Body sub-scale prototype awaiting testing in NASA Langley Research Center's full-scale wind tunnel in May 2006. (NASA photo ED06-0070-2)

Supersonic Research

Interest in a supersonic airliner had dwindled by the end of the 20th century. But in the evolving dynamics of the aviation industry, airliner technology now often lagged behind that of business jets. Business aircraft manufacturers were smaller companies that tended to have shorter product cycles than behemoths like Boeing or Airbus, which helped give them greater agility when it came to integrating new technology. They also had a customer base that was not only willing to pay for improvements in speed, capability, and comfort, but actually demanded those advances. So while the airlines might not have seen an immediate return for developing an environmentally acceptable supersonic transport aircraft, the business jet manufacturers were more interested in the concept. So was the military, although for different reasons. A sonic boom is a telltale sign of an aircraft's presence. One of DARPA's recent projects, therefore, was a *"Quiet Supersonic Program"* which the military research agency hopes will lead to the development of a long-range supersonic bomber with a greatly mitigated sonic boom footprint.



This modified Northrop Grumman F-5E served in 2002-2003 as a Shaped Sonic Boom Demonstrator, showing that the shape of an aircraft's nose could affect its sonic boom. (NASA photo EC03 210-1)

In the Active Aeroelastic Wing project, an F/A-18A rolls upside down during a 360-degree aileron roll during a flight on February 7, 2003. (NASA photo EC03-0039-14)

As part of that program, DARPA and Northrop Grumman joined forces with Dryden to conduct a series of flight research experiments with a highly modified U.S. Navy Northrop F-5E fighter in 2002 and 2003. The nose of the F-5 had been radically altered, so that it looked more like a pelican's beak instead of a traditional pointy-tipped, supersonic fighter. Dryden then flew its F-15B testbed aircraft behind both a standard F-5 fighter and the modified F-5E in various flight conditions to measure how the altered nose shape affected the aircraft's sonic boom. Dryden already had experience in taking ground and airborne sonic boom measurements using an F-16XL in trail behind one of the center's SR-71 Blackbirds to collect data on its sonic boom pattern. The F-5E flights, however, were the first to prove that altering the nose shape of an aircraft could, in fact, mitigate the impact of its sonic signature on the ground.

Homeland Security

A pelican nose shape was not the only approach to the problem, of course. In addition to the F-5 experiments, Dryden also conducted a *"low boom/no boom"* research experiment using two of its F-18 research aircraft to see what impact different maneuvers had on an aircraft's sonic boom pattern and strength. Then in 2005, the business jet manufacturer Gulfstream came to Dryden and asked if the center could help it conduct flight experiments with an extendable, 30-foot-long, composite nose boom that the company's research engineers had developed. In theory, the morphing nose boom could be extended to mitigate a supersonic business jet's sonic impact over sensitive areas, and then retracted for more efficient cruise flight operations over water. Working as equal partners in the project, Dryden engineers and technicians installed Gulfstream's *"Quiet Spike"* design on the nose of Dryden's F-15B testbed aircraft, and the first flights of the experimental configuration were slated for the second half of 2006, as this book went to press.

The Gulfstream/Dryden partnership was a good example of how Dryden's experience in flight research could be a valuable asset to a manufacturer that, unlike Boeing or Lockheed Martin, did not typically conduct major flight research experiments. Gulfstream had the initiative and desire to advance the state of the art in business aircraft design. But the company was not accustomed to researching radical configurations in flight. By partnering with Dryden, however, Gulfstream could gather the data it needed to push ahead with its entrepreneurial vision in a safe and successful manner.

Dryden's F-15B research testbed with Gulfstream's Quiet Spike retractable nose boom. (NASA photo ED06-0111-05)

NASA research pilot Gordon Fullerton checked out how the PCA software worked in the multi-engine simulator at Ames Research Center before flight-testing PCA in an MD-11. (NASA photo ED05-0092-01)

The other area of aeronautical research that was gaining support outside of NASA related to some of the Propulsion Controlled Aircraft (PCA) and neural network research that Dryden had conducted with various research aircraft throughout the 1990s. In the post-9/11 world, addressing the threat of missile strikes or other terrorist attacks on transport aircraft suddenly became a much higher concern. So, with support from the Department of Homeland Security, Dryden revisited its research with both of those adaptive technologies. In one effort, Dryden engineers began exploring a Propulsion Controlled Aircraft Recovery System (PCARS). The first step in the effort focused on developing a checklist to help a pilot control a damaged aircraft by use of throttles alone, without any modification to the aircraft. The eventual goal of the PCARS research, however, was to certify an automatic propulsion-only control system that would enable an autopilot system to fly an aircraft with damaged flight controls back to a safe landing.

A second research effort, called Damage Adaptive Control Systems (DACS), was an extension of Dryden's earlier work in self-repairing flight controls and intelligent flight control systems. The goal of the DACS research was to explore, at least in simulation, how an adaptive, integrated flight control system might react and adjust successfully to the damage a missile or other attack might inflict.

Future Directions

Interestingly enough, air carriers within the U.S. were, at least initially, only mildly interested in the PCARS or DACS technology. Several cargo carriers who operated at high-risk airports in the Middle East, on the other hand, were extremely interested in the concepts. Those different levels of interest are not hard to understand, of course. Need is a critical element in the willingness of a manufacturer or operator to implement new technologies that other people invent.

Future Directions

If Dryden managers and staff have learned nothing else from the past decade's events, they have learned that all plans, projects, and directions are subject to change at all times. In truth, that has always been the case at Dryden. But there has also been an undeniable increase in the number of project cancellations and directional shifts in recent years. And that increase presents a very real challenge for Dryden in the years to come. Federally funded research is always, to some degree, subject to the changing political climate and cycles of the nation's government.

Dryden's F-15B research testbed (left) in formation flight with the F-15B ACTIVE. (NASA photo EC05 0148-04)

Of course, for a research institution's work to remain aligned with, and relevant to, the nation's priorities and needs, it's critical that it be able to make course corrections as the world and outside events change and evolve. But maintaining a healthy research base for both the nation's current and future needs involves a tricky and delicate balancing act. Clearly, researchers need to respond to the near-term needs of industry and the nation. But if research projects are focused only on immediate priorities, long-term research gets neglected, weakening the nation's capability for technology advances farther down the road, especially in complex technology areas. It's difficult to see in the moment how serious that impact might be.

Maintaining a healthy balance between near-and far-term research efforts is also harder at times when it isn't entirely clear what the future technology needs of the country are going to be. During the Cold War, the direction and focus of U.S. aerospace technology was driven, at least in part, by parallel advances the Soviets were making in aviation and space. In today's world, there isn't such a clear, driving imperative or direction in either space or atmospheric flight. Clearly, improvements in systems, safety, and efficiency are still important, as is exploration to better understand our planet and its relationship to the rest of the cosmos. But what amount of funding and support should be allocated to each area, and to any given concept within each area? These questions aren't easy to answer, and trying to create and retain support for balanced and productive research efforts that address the nation's needs in both the immediate and distant future is going to remain one of the bigger challenges for not only Dryden's managers, but for NASA as a whole.

Dryden's relationship with its various industry and external partners has also always been a work in progress, and one that entails its own set of challenges in terms of balance. If Dryden's research efforts stray too far from the priorities and needs of industry, it risks becoming irrelevant to the very entities that would turn those advances into practical vehicles and systems. On the other hand, the financial constraints of private industry tend to force companies to look at quicker returns on investment than a governmental research institution. NASA and Dryden have not only the luxury, but also the serious obligation and responsibility, of looking beyond the next profit quarter to insure a healthy science and technology base for the nation's future.

Middle Ground

Ironically, Dryden's integral connection with real-world hardware and flight, which positions its work far closer to tangible, practical applications than work typically produced at laboratories devoted to more basic research or NASA centers devoted to the scientific exploration of space, has proven to be something of a doubled-edged sword. On the one hand, Dryden can point to many projects that, in fairly short order, resulted in improved technology or commercial products – results that clearly underscore the relevance and impact of the center's efforts. On the other hand, the directness of that link leaves Dryden susceptible to criticisms of providing too much assistance to industry.

Maintaining the correct middle ground between the extremes of irrelevance or what is sometimes termed *"corporate welfare"* will undoubtedly become more challenging as Dryden expands its base of external research partnerships. But to even attract those partners, Dryden also has to work harder at maintaining a workable balance between its own operational style and that of its various partners and customers. The research engineers at the NACA and NASA have not always seen eye-to-eye with research partners whose goals differed from the data gathering that was always the prime passion and mission at the NACA and NASA, or with partners who had different standards for safety or thoroughness. As center director Kevin Petersen put it, *"People come here for our expertise, experience, and advice. But sometimes they may get more of that than they want, and we need to adapt to our customers' requirements."*[3]

Clearly, a balance is necessary when it comes to how projects are vetted, planned, and executed. But it's difficult to know exactly how much margin, in terms of ensuring flight safety or mission success, is enough. After many years of accident-free flight, the X-31 crash in 1995 was a sharp reminder for everyone at the center that flight research was still a hazardous endeavor. And, in truth, one of the reasons that Dryden is sometimes recruited to help troubled flight research projects get back on track is explicitly because the center is so good at understanding and managing risk factors – not only for flight safety, but also for mission success. So the challenge for Dryden is figuring out how to inject additional flexibility into its historically stringent safety and mission procedures – especially in a world where more research aircraft will be remotely piloted – without compromising its ability to shepherd flight research projects safely to successful conclusions.

To meet these challenges, of course, require Dryden's managers and employees to bring even more flexibility and innovative thinking to the tasks at hand than they have in years past. In a sense, the past has been but prologue to the future. As the pace of change in the world has hastened, the need for Dryden's bedrock strengths of technical agility, flexibility, and innovative thinking has grown, as well. And somewhere in that equation, there is the challenge for Dryden to keep the same edge it had when the center was young – to keep alive a thirst for discovery, a willingness to take on risk and uncertainty, and a passion for exploration, regardless of the project, vehicle, or application.

To be sure, the challenges facing Dryden are great, and the effort to meet them will not be easy. But in a 1962 speech on why the nation should take up the immense challenges of space exploration, President John F. Kennedy quoted another pioneer embarking on a great and unknown adventure. *"William Bradford,"* Kennedy said, *"speaking in 1630 on the funding of the Plymouth Bay Colony, said that all great and honorable actions are accompanied with great difficulties, and both must be enterprised and overcome with answerable courage."* And while the world of the early 1960s sometimes seems a simpler and easier place than the world we live in now, Kennedy also told his audience on that September morning that *"we meet in an hour of change and challenge, in a decade of hope and fear, in an age of both knowledge and ignorance. The greater our knowledge increases, the greater our ignorance unfolds."*[4]

Engineers Paul Lundstrom, left, and Larry Reardon monitoring forces applied by structural loads equipment to a Navy E-2C Hawkeye aircraft in a successful joint effort to help the Navy determine how the Hawkeye will respond to the additional weight that planned modifications will add to the aircraft. (NASA photo EC04-0360-74)

The fact that Kennedy's words are as fitting today as they were 44 years ago only illustrates why, despite all the advances in simulation, computer modeling, and technology, the need for a facility like Dryden still exists. We have learned much about operating off the surface of the Earth since the advent of flight. But President Kennedy was correct. The greater our knowledge increases, the greater our ignorance unfolds. We know how to reach supersonic speeds, but there is still a tremendous amount we don't yet understand about the forces and dynamics of transonic, supersonic, and hypersonic flight. Advances in materials and computer technology have opened doors to entirely new aircraft and spacecraft configurations, as well as integrated systems that may revolutionize the design, operation, and safety of both military and civilian aircraft. But those same computers also bring with them new challenges and problems. Slow speed, high-altitude flight is still a largely uncharted territory. The UAV industry has advanced by leaps and bounds in the past 10 years, but there are still a great many developments and issues to be explored and resolved as more of those aircraft take to the skies, high among them flying seamlessly co-mingled with piloted private and commercial aircraft.

In a series of flights in the summer of 2005 at Dryden, researchers such as Michael Allen (shown here with a powered sailplane) validated the assumption that thermal lift could significantly extend the range and endurance of small unmanned aerial vehicles (UAVs)—offering further possibilities for development to the UAV industry. (NASA photo EC05-0198-11)

And while the aerospace industry can and will explore and answer some of those questions, industry alone cannot be expected to carry the entire burden of advancing the nation's accomplishments, knowledge, and understanding of flight. The success of the commercial satellite industry, the growth of the UAV market, and even Scaled Composites' successful *"SpaceShipOne"* flight in 2004 clearly illustrate the ability of private industry to accomplish much in aeronautics and space. But there are still critical areas of aerospace research – including efforts related to safety or with very uncertain but potentially high payoffs – that industry lacks either the ability or motivation to pursue. Small, entrepreneurial companies, with limited research funding and the need for fairly quick development cycles, often don't have the luxury or ability to work on long-term problems. In addition, there are important technologies that are simply too immature, or too high-risk, for industry to incorporate into a production vehicle or product without the risk-mitigating evidence and confidence that a flight research program provides. There are also data-gathering technologies and missions, such as those related to the health and stability of our planet's climate, terrain, or resources, that benefit society and decision-makers far more than they will ever benefit any particular industry. Not to mention, of course, research and development to support the space exploration efforts the nation decides to pursue.

We have learned much, and our tools have grown much more sophisticated. But as the problems become better understood, the underlying complexity has revealed the need for more sophisticated tools. So the need for explorers and researchers willing to dedicate themselves to solving those problems – and the need for well-supported research facilities to aid in those efforts – is as great as it ever was. The extraordinary expertise, hardware, and unique flight research facilities and platforms at Dryden may not seem like irreplaceable national assets, but the truth is that they are. If, for lack of funding or support, good people at Dryden leave, or the center's testbed aircraft are sent to the bone yard, the capacity of Dryden to conduct a successful X-plane research, support industry's efforts to advance technology, help NASA develop new spacecraft designs, or even support efforts to make existing aircraft or spacecraft safer, will be compromised. And, if lost, those assets will be difficult if not impossible to restore.

Conclusion

The Dryden Flight Research Center may have begun as a small research task force dedicated to a single project and goal. But it quickly evolved into a national research facility that is still a vital national resource. Its clear skies, open landscape, and lakebed landing sites have allowed numerous flight activities to take place there that could not have been accomplished elsewhere. Its small size, pragmatic focus, and its informal, flexible, innovative style of management and operation have helped encourage the development of a staff infused with both technical passion and technical agility – traits that have allowed the center to support a wide range of research programs and priorities, as well as adapt to the constantly changing times and priorities of the past 60 years.

Dryden's unique ground and airborne flight research facilities and testbeds have enabled academic institutions, small entrepreneurs, and critical national agencies to explore and develop a host of new concepts and technologies. The passion and creativity of Dryden's research staff has led to innovations ranging from a lifting body spacecraft design to a method for landing a crippled airliner safely. The combined flight research expertise and experience of that same staff has played a critical role in troubleshooting problems in vehicles ranging from transport aircraft and supersonic fighter jets to the space shuttle. Time and time again, Dryden has joined forces with industry, academia, and other NASA centers and government agencies to probe the edge of the unknown in a never-ending effort to expand our horizons, understanding, and capabilities in both atmospheric and space flight.

Flight research is unique. It is an area where researchers are forced to correctly identify which problems associated with a concept or technology are truly critical to solve for flight. It also requires integrating individual components into hardware and systems that often perform differently in combination, and in the real world, than any computer could predict on the ground. It requires constant teamwork and flexibility, both across research disciplines and also among the various manufacturers and agencies involved in complex flight research efforts.

But the challenges of taking a concept to flight are also part of the reason that the results are so effective. Flight can bridge the gap between laboratory research and application of a piece of technology, both by maturing the technology in the process of taking it to flight, and by demonstrating the effectiveness of a concept in a real-world situation. The technology may still prove impractical, but once it has been proven in flight, few can argue that it can't be done. And because flight research puts technology into that ragged boundary area between what is known and the mysteries that lie beyond, it is a place where discovery happens.

Two of Dryden's F/A-18s flying in formation as part of the Automated Aerial Refueling project. The goal was to demonstrate that, when using special software and hardware, the trailing aircraft could engage the basket and take on fuel without pilot involvement. The objective was to enable one UAV to refuel another UAV without human control. (NASA photo EC03-0293-06)

Conclusion

The road to those precious moments of discovery is not an easy one, of course. No matter how well engineers and analysts try to anticipate every possible problem and reaction, physical exploration of the unknown is never without risk. If the results of flight research are significant and incontrovertibly real, so are the consequences of any mistake. And yet, the importance of a place, and a group of people, who are willing to take on that task and risk is incalculable. For it is the courage of people willing to step into the lonely abyss of the unknown – from Wilbur and Orville Wright launching the first powered, controllable airplane, to Dryden center director Paul Bikle authorizing the construction and flight of the first M2-F1 lifting body, to pilot Gary Krier flying the first digital fly-by-wire aircraft, to Neil Armstrong taking the first human step on the moon – that has allowed progress to occur.

"We do [these] things," President Kennedy said in 1962, *"not because they are easy, but because they are hard."*[5] For over 60 years, the Dryden Flight Research Center has been a place where *"hard"* problems have been welcomed. It is a place where people are encouraged to question and to look for the unexpected where it is understood that the answers exist and the challenge is to find them. The center's priorities and projects have changed; its challenges have evolved. But by persevering through all those challenges and changes, Dryden has enabled countless advances that have saved lives, led to the design of better and more capable aircraft and spacecraft, and expanded our understanding of the world and the atmosphere that surrounds it.

The Mojave Desert may be windy and desolate. Yet for all its desolation, the desert also contains unique gifts. It offers unending days of piercing blue skies; dawns and sunsets that dust its rocky mountainsides with breathtaking hues of color. And while its arid landscape and dry lakebeds support sparse vegetation, for the past 60 years they have provided an ideal environment for pilots, researchers, and engineers to test and explore new concepts in flight. Cradled in the midst of that ideal desert world, the Dryden Flight Research Center has already contributed to the birth of countless discoveries that have revolutionized aerospace technology. But the more we know, the more we realize how much there is still to learn. So the journey – and the need for courageous explorers willing to undertake the challenges of that unpredictable and constantly changing journey – continues. For somewhere beyond the boundaries of what is known, the future still awaits.

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1 Summary report of the House of Representatives Committee on Science and Astronautics recommendations affecting NASA for FYs 1964, 1965, and 1966, May 25, 1966, from Richard Hallion files in the Dryden Flight Research Center Historical Reference Collection, Edwards, California.

2 Griff Corpening, interview with author, June 15, 2005, Edwards, CA.

3 Kevin Petersen, phone interview with author, May 10, 2006.

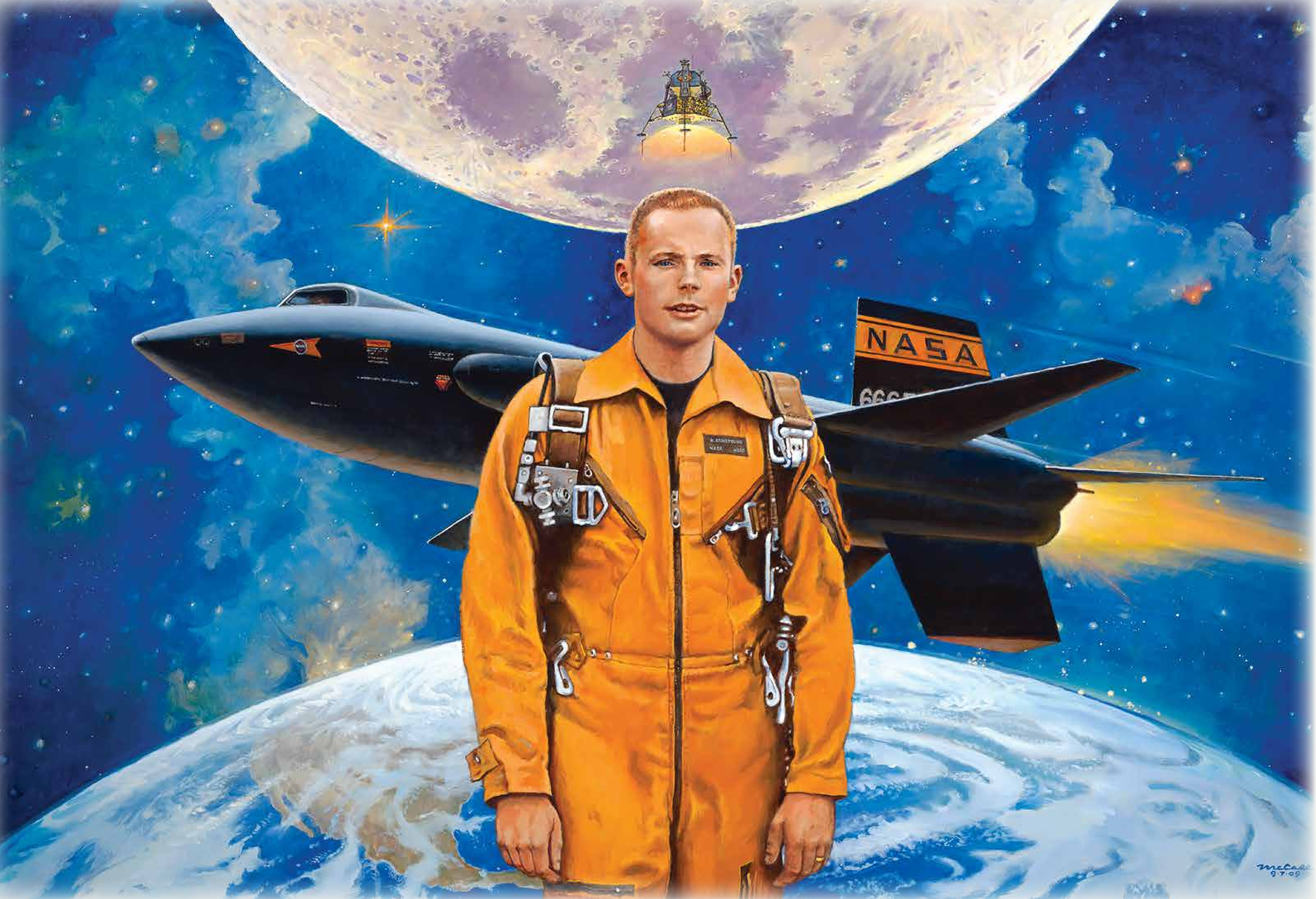
4 John F. Kennedy, address at Rice University, Houston Texas, September 12, 1962 (transcript available from various sources, including http:://webcast.rice.edu/speeches/19621912kennedy.html)

5 Ibid.

A NASA F-15B aircraft with insulation from the space shuttle external tank in 2005 to test for the shedding of foam pieces as part of the effort to return the shuttle to flight — an example of Dryden's role in troubleshooting problems for the Agency. (NASA photo EC05 0030-12)a

Chapter 9

A New Name



The Real Right Stuff

by Robert McCall

Armstrong Flight Research Center

On May 13, 2014, the Dryden Flight Research Center was formally renamed the Neil A. Armstrong Flight Research Center in honor of Neil Armstrong, a pilot at the center and the first human to set foot on another celestial body. President Barack Obama signed congressional resolution H.R. 667 on Jan. 16, 2014 changing the name. Dignitaries attending the ceremony included NASA Administrator Charles *"Charlie"* Bolden, U.S. Congressman Kevin McCarthy (California), state senator Steve Knight (son of X-15 pilot William J. *"Pete"* Knight), Rick Armstrong (son), Janet Armstrong, Andrew Armstrong, Wendy Armstrong, Kali Armstrong, Mark Armstrong (son), Matthew Hugh Dryden (Hugh Dryden's great grandson), Tristan Dryden, Logan Dryden, Eric Dryden (Hugh Dryden's grandson) and Lisa Dryden.

"It was an honor to share the Dryden name with this amazing test facility and all of its employees here at NASA for the past 38 years," said Eric Dryden. *"I knew my grandfather for five months before he passed away, but I know he would be extremely proud and honored to pass the torch to an amazing engineer, test pilot, astronaut and true aerospace pioneer Neil Armstrong."* The center's Western Aeronautical Test Range was renamed the Hugh Dryden Aeronautical Test Range.

"He considered himself an engineer first," said Rick Armstrong. *"He said science is about what is and engineering is about what can be."* Rick Armstrong said his father would be proud to have his name on the NASA facility to continue inspiring young people in science, technology, engineering and mathematics so they can achieve great things like those accomplished at the center.

Ikhana

NASA acquired a General Atomics Aeronautical Systems Inc. (GA-ASI) MQ-9 Predator B unmanned aircraft system (UAS) in November 2006 to support Earth Science missions and advanced aeronautical technology development. Named Ikhana by NASA, the aircraft also served as a testbed to develop capabilities and technologies to improve the utility of UAS. "Ikhana" is a Choctaw word meaning intelligent, conscious or aware.

Pilot Stu Broce is pre-breathing 100% oxygen prior to take off for an Air-LUSI flight in NASA's ER-2 at Armstrong Flight Research Center. NASA AFRC2019-0270-401

IKhana

GA-ASI developed the original Predator A medium-altitude, long-endurance UAS during the mid-1990s for the U. S. Air Force. Work on the larger, more powerful Predator B began in 2000, partially funded by NASA under its ERAST program: the agency was interested in the Earth science capabilities of a civil version of the aircraft with a larger payload and higher altitude capability, as well as longer endurance. (Ikhana and Orion capsule splashdown)

Carrying a custom imaging sensor pack, Ikhana participated in the Western States Fire Missions between 2007 and 2009 by overflying numerous very large forest fires and gathering data for use on the ground. NASA Ames Research Center developed the sophisticated Autonomous Modular Sensor (AMS) and real-time data communications equipment. The AMS could see through thick smoke and haze, finding hot spots and the progression of the fires. That data was overlaid onto Google Earth maps, downlinked in near real-time to the Interagency Fire Center in Boise, Idaho, and made available to fire incident commanders to assist in allocating firefighting resources.

Ikhana in flight over the Antelope Valley, California, where Edwards Air Force Base and NASA Armstrong are located. (NASA photo AFRC2018-0115-39)

Ikhana was the platform for the development and integration of a Fiber Optic Sensing System (FOSS), a new way to measure structural loads on an aircraft in flight. An early version of FOSS was built and integrated onto a NASA F/A-18 in 1999 (the Systems Research Aircraft, tail No. 845). Principal investigator Lance Richards advocated using the aircraft to reduce risks associated with its eventual integration onto the X-33 demonstrator (to which the Flight Loads Laboratory contributed support on composite propellant tanks; X-33 never flew). But the FOSS' laser did not function in flight, generating no data. After that setback, NASA decided to develop FOSS within the agency, based on the experience at Armstrong's Flight Loads Laboratory, to develop ground-based strain gauge data acquisition systems. Ikhana was the first aircraft to gather FOSS data in flight (strain, temperature and wing shape).

The NASA-patented FOSS moved from years of laboratory development and testing to large-scale, dynamic field testing in 2008, when FOSS first flew on Ikhana to measure various strains on its wings.

In support of the agency's Unmanned Aircraft Systems Integration in the National Airspace System (UAS-NAS) project, Ikhana first flew an Automatic Dependent Surveillance-Broadcast (ADS-B) system in 2012. ADS-B is an aircraft tracking technology that allows aircraft with the system to see and track other ADS-B-carrying aircraft in the area. The Federal Aviation Administration (FAA) mandated ADS-B be carried on virtually all aircraft in the U.S. by 2020.

More extensive support of the UAS-NAS project followed from 2014 to Ikhana's retirement in 2018. The UAS-NAS project partnered with the FAA, GA-ASI, Honeywell International Inc. and Aviation Communications and Surveillance Systems (ACSS) to support multiple flight test series using Ikhana while flying out of Edwards Air Force Base. The purpose was to engage the core air traffic infrastructure and supporting software components through live and virtual environments to demonstrate how a remotely piloted aircraft interacts with air traffic controllers and other air traffic while using ADS-B.

In June 2018, demonstrating the application of the minimum operational performance standard (MOPS) in flight, Ikhana became the first aircraft to obtain a No Chase Certificate of Waiver Authorization (COA) from the FAA, and successfully flew a six-hour mission through multiple classes of civilian airspace (A, D and E) without the support of a chase plane or visual observers heretofore required for a UAS operating in the NAS.

AAM and UAS-NAS

Pilots flew Ikhana from a ground control station (GCS) via line-of-site radio frequency communications as well as satellite links for over-the-horizon communication. The GCS was mobile, facilitating deployment operations. Aviation Week & Space Technology selected Ikhana's No Chase COA flight as a winner of its 62nd Annual Laureate Awards.

AAM and UAS-NAS

Advanced Air Mobility, an overarching program that includes unmanned aircraft systems in the National Airspace, is designed to help emerging aviation technology and new markets fit into and work with the national airspace.

An Armstrong pilot chasing Ikhana in one of the Center's King Airs during a UAS-NAS project flight. (NASA photo AFRC2018-0115-31)

Medicine and supplies might be delivered into remote areas of the world where terrain and access are difficult. Rescuers working in areas hit by natural disaster could benefit from such aircraft in finding survivors. An item purchased online could be on its way to a customer's door in mere hours. These are some of the visions for how UAS might be used one day when such vehicles have routine access to the NAS. For more than four decades Armstrong has had a hand in the development of unmanned aircraft systems and continues to have a role in the critical steps needed to incorporate them into the same airspace as piloted aircraft. (UAS-NAS)

In order for a commercial market to flourish for UAS, a number of FAA requirements must be met. Many of these FAA integration requirements are still in development and NASA and Armstrong have a major role in that process. UAS-NAS project provides recommendations to the FAA to establish rules, regulations and limit risks. UAS can range in size from tiny vehicles just inches long to as large as a commercial jetliner.

"The path the FAA is going down will allow small UAS first to have access into the NAS. Safe access might include a finite part of the national airspace at first" said Laurie Grindle, Armstrong Director of Programs and Projects. *"The key word is routine access, the same kind of access a manned aircraft has to the NAS. You won't have to plan six months in advance the exact path you want to fly, or exactly the mission you want to fly,"* she added. Ultimately, filing a flight plan will be the process and will eliminate the need for the special agreements (called certificates of operations, or COAs) currently used that require a lead time of up to six to eight months for a single flight. Phase 1 of the project was completed in 2016, and it is expected the FAA will use those recommendations in developing rules and policies for making UAS access to the NAS happen.

In a manned aircraft *"there is a person in the cockpit that can see an aircraft and avoid it. But with the pilot being in the ground control station, and not in the aircraft, you don't have someone who is seeing and avoiding all the other aircraft. Now you have to come up with a new definition of 'well clear,' i.e. maintaining an appropriate distance from other aircraft, but a definition that is one a system can achieve,"* added Grindle. (UAM)

AAM and UAS-NAS

The current effort builds on the Center's previous work, such as the ERAST program and the Access 5 effort that followed.

A two-month long flight test series concluded in 2016, marking an essential stage in the agency's research into technologies that support safe integration of UAS into the NAS. To test two safety algorithms, more than 260 scripted encounters were performed between the Ikhana and manned *"intruder"* aircraft. These intruders included NASA's B200 King Air, T-34C, GIII and TG-14 aircraft, a Honeywell C-90 King Air and a U.S. Air Force C-12 King Air (B200). The intruders were equipped with different surveillance systems that identified them as either cooperative or non-cooperative aircraft, which is a real-life aspect of NAS operations. Cooperative aircraft include those intruders capable of sharing their location, such as an ADS-B system, Traffic Alert and Collision Avoidance System (TCAS) or a transponder facilitating traffic detection and resolution. Non-cooperative aircraft refer to intruders that either are not equipped with these systems, or have system failures and require an alternative means of detection. In addition to pilot intervention, a number of encounters tested the system's interoperability with automatic collision avoidance maneuvers, performed using TCAS. The TCAS maneuvering was one of the objectives for testing and the collision avoidance performed successfully. AAM is meant to help the FAA develop new rules essential to that market's access to the NAS, and thus, its growth. The program is also meant to nurture the emerging technology at the root of this new direction in flight. (AAM)

Flight Loads Laboratory

Armstrong's Flight Loads Laboratory (FLL 50th anniversary) has existed by one name or another since 1964. Its initial work was to test thermo-structural aspects of the X-15. Demonstrating its importance, the center began sending all manner of things to the laboratory for testing. Through the decades the laboratory acquired the ability to test composite materials destined for high thermal and structural stress, such as on space-bound vehicles. It has one of, if not the best capabilities in the agency and regularly draws outside customers for that reason.

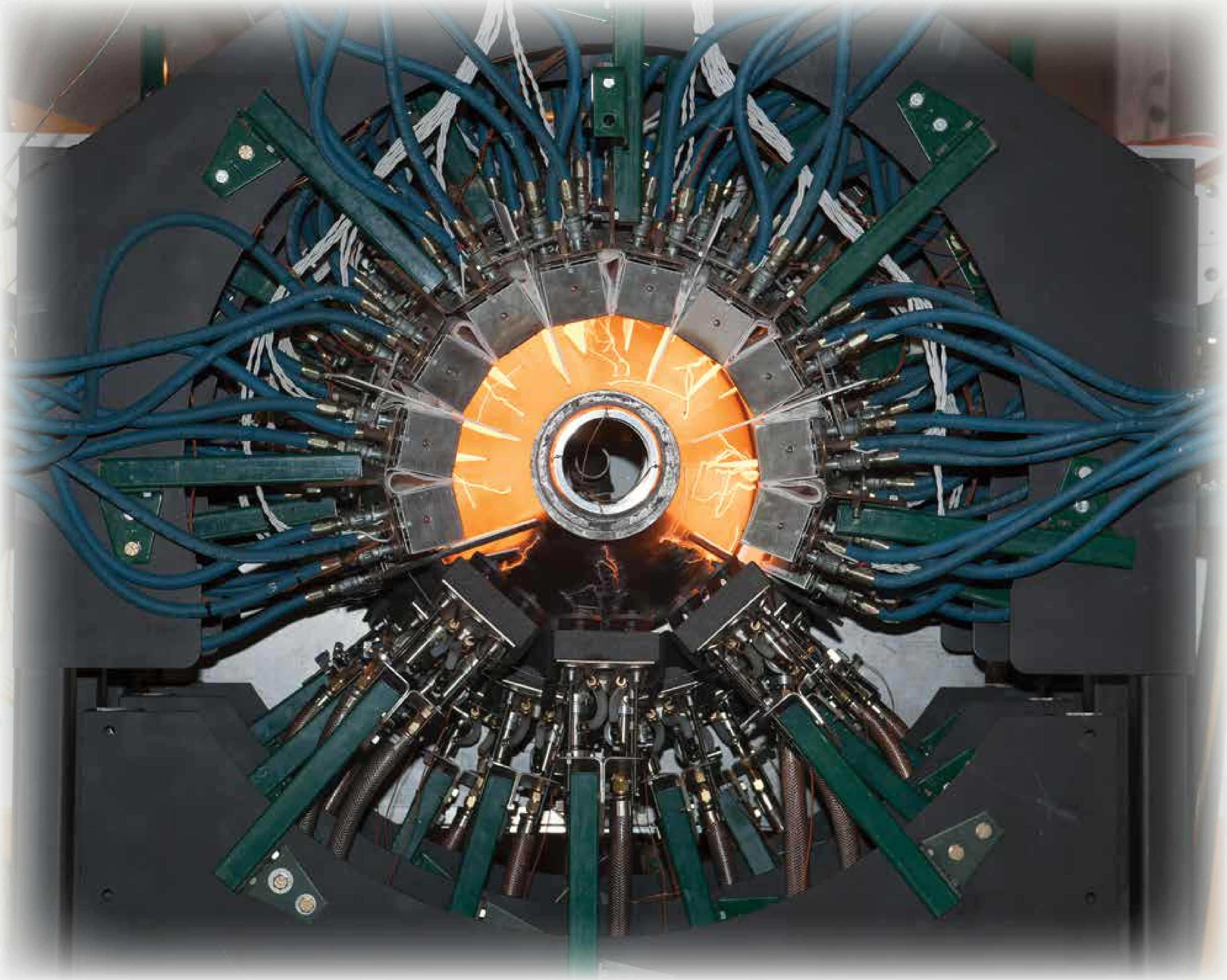
In 2010 the laboratory performed the loads test on a wing for AeroVironment Inc.'s Global Observer-1, a hydrogen powered, propeller-driven high-altitude, long- endurance aircraft with an immense wingspan. "The purpose of the test was to monitor the strain of the wing panels under load, and to monitor the wing shape of the panels using the NASA-patented wing shape algorithm. Eighteen fibers, each with as many as 1,000 fiber Bragg grate sensors, were bonded to the forward and aft portion of both wings. You can get the information you need from the thousands of sensors on a few fibers without the weight and complexity of conventional sensors. Strain gauges, for example, require three copper lead wires for every sensor," said Lance Richards. Contrast that to 30-years ago, when "you might have 12 or 20 accelerometers and would shake the airplane (during a ground vibration test) and someone would look at a scope and get a voltage – it was extremely time-consuming." AeroVironment, like companies and universities before it, came to the center's laboratory for such work because of the facility's unique capability as well as its workforce experience.

Between 2013 and 2014 the laboratory, in cooperation with Langley, tested the Hypersonic Inflatable Aerodynamic Decelerator (HIAD), a set of highly pressurized, inflated rings of different sizes; when inflated and stacked they form a wide cone. Armstrong's Larry Hudson explained the logic of HIAD: "If you want to take a large mass to other planets to support human exploration, we have to go beyond the current technology that limits the size of the heat shields that can be carried. Inflatable systems allow us to carry bigger systems, to decelerate larger masses." Set in a stand, a HIAD toroid had 33 straps attached to cables that could be pulled toward a center pillar with sufficient force to deform the inflated toroid.

The laboratory's Matthew Moholt began working with engineers and scientists at NASA's Glenn Research Center on shape-memory alloys (SMAs) as possible replacements for actuators. While the material in its most rudimentary form dates to 1932, its possible applications are only now emerging. Nitinol, the generic name for a range of alloys, most of which contain nickel and titanium (and some other metals), exhibit remarkable and unusual capabilities, not least of which is the ability to be "trained." "Materials that can change shape with the application of heat," said Moholt, "psuedoelastically deform, take large strain and return to their original shape as well." Piezo-electrics have high excitation rates but exert little force; SMAs have low response but can generate immense force for their weight or energy input – great work out-put, offering an alternative for high-torque needs.

Flight Loads Laboratory

At the turn of the new century, the Flight Loads Laboratory added such features as graphite heaters able to reach temperatures in excess of 2,500 degrees Fahrenheit (home ovens reach 500 degrees Fahrenheit), and a 24 feet x 24 feet x 10 feet nitrogen chamber. At this writing the laboratory has a variety of ovens, one that is programmable and capable of holding specimens up to 4 feet 3 inches and a temperature of 2,000 degrees Fahrenheit, others that are manually controlled with temperatures ranging from 650 degrees Fahrenheit to 1,300 degrees Fahrenheit.



The Flight Loads Laboratory's graphite heater in operation.(NASA photo ED10-0289-2)

In 2019, the laboratory took on two series of structural tests on a uniquely designed, high-aspect-ratio, lightweight experimental wing built to demonstrate a new method of wing design and fabrication. Karen Taminger, an Advanced Air Transportation Technology project technical lead at NASA Langley explained the Passive Aeroelastic Tailored (PAT) wing could enable longer, thinner wings that maximize structural efficiency, reduce weight and improve fuel efficiency. The idea is to passively control flutter through a structural design that can also help minimize gusts for a smoother ride for passengers. Technicians added 11,000 sensors to the wing, making it *"the most highly instrumented wing we have ever tested,"* said Hudson. The Loads Laboratory designed a special test fixture along with a series of underwing actuators, overhead hydraulic actuators and cables so that loads simulating distributed air pressures could be applied to the wing.

In 2014, the Loads Laboratory performed loads and stress tests on the GIII carrying the Active Compliant Trailing Edge (ACTE) flap.

The X-57 wing being load-tested in the Flight Loads Laboratory. This is a new wing, replacing the original Tecnam P2006 wing. (NASA photo AFRC2019-0215-40)

Foss

Center engineer Lance Richards began considering fiber optic applications to aerospace in the 1980s and saw potential in work being done at NASA's Langley Research Center in the mid 1990s. Along with William Ko, Anthony "Nino" Piazza and Allen Parker, the team at Armstrong began to adapt the existing technology for aerospace use, developing the algorithms, hardware, software and ideas to make it functional. In 2008, they built and integrated a Fiber Optic Sensing System (FOSS) onto Ikhana, the center's remotely piloted Predator B. Flights demonstrated that FOSS could provide real-time wing shape sensing predictions and worked as well in the sky as it had in the laboratory. Since then, the team has worked to simplify the system while improving reliability. "Once we saw this fiber react to the environment, we knew this had the potential to change the way we do structural health monitoring, but we also knew we had a long road ahead," Parker said of early research. (Parker and FOSS)

Fiber optic Bragg Grating, the essential element of FOSS, entails fabricating fiber optic filaments with "Grates" in them at discrete points along the filament. Each Bragg Grate is designed to reflect a certain light wavelength while letting other wavelengths pass through. Shooting a laser down the filament and measuring the reflections from the gates allows one to, for example, know when and where the filament is deflected by a load. This translates into strain sensing. When integrated across a wing, FOSS can tell the researchers when and where a load was imposed on the wing, how much of a load and for how long, all by the deflection of the fiber. In the past, collecting structural data and transmitting it required miles of wires, harnesses to keep the wires in place, and bulky sensors that added weight and complexity to aircraft systems. Traditional strain gauges are comparatively heavy and must be spaced much further apart than Bragg grates. A 40-foot hair-like optical fiber, in contrast, provides up to 2,000 data points, a dramatic improvement over conventional strain sensors in every respect. The potential to measure strain on an aircraft during flight offers aircraft health monitoring in real time is enormous.

With the combination of smaller size and faster data transfer, the FOSS has been proven on NASA Ikhana, AeroVironment's Global Observer and is carried on the X-56.

Applications of FOSS are much wider than just aeronautics, extending to space, medicine and drilling, for example. Parker believes a day will come when aircraft are built with fiber optics embedded in them and have systems that tell maintainers exactly what is wrong, without extensive – and expensive – maintenance down periods. *"Like a human nervous system, which has 'sensors' embedded throughout the body from the legs, arms, back and all areas, and which determine the state of the body, then feeds that information to the brain – the same is true for this next-generation aircraft system,"* said Parker. He also developed an algorithm that permits information from fiber optic sensors to move exponentially faster. The initial rate of information transfer from fiber optic sensors in the past was one sample every 30 seconds; Parker's algorithm increases that to 100 readings per second. The team also worked on miniaturization of fiber optic sensor systems.

NASA
DRYDEN FLIGHT
RESEARCH CENTER
sUAS Research Laboratory

The APV-3 remote piloted aircraft on Rosamond Dry Lake at Edwards. Note the numerous individual control surfaces that can be activated independently for gust load alleviation. ED14-0047-15)

Shuttle Retirement

The FOSS team has also worked with NASA's Marshall Space Flight Center to refine the system for launch vehicles. In addition, NASA's Aeronautics Research Mission Directorate's Flight Demonstrations and Capabilities project is funding elements of FOSS work to increase the technology readiness level (TLR). It is envisioned that a FOSS could collect information on how aerodynamic forces are affecting an aircraft in real-time and loop that information directly into the aircraft's control system for fuel efficiency, safety and a more comfortable ride for passengers. FOSS has also been touted as a monitor of liquid propellant levels and the temperatures and the strain on spacecraft. The NASA Engineering and Safety Center also is interested in using a FOSS in the construction of composite fuel tanks to gather data on the physics of what is actually happening in real-time to the tanks. Industries such as oil, gas and dairy have inquired about a simpler system that can help with a number of different applications. The center's Technology Transfer Office (TTO) is leveraging those solutions to benefit a wide range of non-aerospace industries: two licenses have been granted and five more are pending for evaluation of liquid level sensing in the beverage industry, liquid level and cryogenic liquid level testing, evaluation for 3D shape sensing for robotic surgery applications and strain and shape measurements for the automotive industry.

The Armstrong FOSS team is developing the next generation of FOSS, called micro FOSS, a more compact, economical and robust version. The effort is in partnership with the U.S. Navy and has expanded to include monitoring the stress loading on its vessels that transport a heavy load, such as aircraft and tanks. The Navy wants to monitor stress loading on the hulls and decks of those vessels.

R&D Magazine named FOSS the winner of an R&D 100 Award, touted as the *"Oscars of Innovation." "The applications of this technology are mind-boggling,"* added Richards.

Shuttle Retirement

Space shuttle Endeavour made one last flight in September 2011 – to its home at the California Science Center in Los Angeles. Before that, however, it flew around much of California atop a NASA 747 Shuttle Carrier Aircraft (SCA).

Endeavour completed its final mission June 1, 2011, the end of a 16-day journey of more than 6.5 million miles. Endeavour marked the first time that an orbiter was named through a national competition involving students in elementary and secondary schools. It was named after a ship chartered to traverse the South Pacific in 1768, captained by British explorer James Cook, whose principal task was to observe the Transit of Venus at Tahiti, enabling astronomers to determine the distance of the Earth from the sun.

Shuttle Endeavour being flown around California on a salute flight – its last time being airborne – before going to the California Science Center for permanent display. In the background is the Golden Gate Bridge. (NASA photo ED12-0317-012)

Fused Reality

People from all around California came out for a glimpse of Endeavour and its host, a shuttle carrier aircraft, as it wended its way from Armstrong to San Francisco and then to Los Angeles, where it flew past numerous well-known sites. The pair made one low level pass down the 25 Left runway at the Los Angeles Airport (LAX), then came in for its final landing. (Enterprise around Los Angeles)

The center had been part of Endeavour's support from its first mission that landed at Edwards in 1992. Endeavour landed at Armstrong/Edwards AFB seven times. Not long after landing at LAX, Endeavour was slowly trucked through the streets of Los Angeles – a huge public event – to its final destination at the California Science Center, where it is on display.

Fused Reality

Fixed-based simulation is an excellent tool that allows pilots an opportunity to train in an unfamiliar aircraft or to gain experience and confidence for a new mission. A disadvantage of simulation has been that the pilot does not have the sense of being in the cockpit, thereby missing some of the cues that come with that experience. Systems Technology Incorporated, or STI, of Hawthorne, California, developed a new simulation system as part of Armstrong's Small Business Innovative Research agreement that can bridge that gap. Called Fused Reality, it allows a pilot to use a fusion of actual flying and a flight environment assembled with live video and virtual reality to provide the most realistic simulation experience currently available. Designed initially as a way to measure aircraft handling qualities, the developers soon saw the potential in in-flight simulation. Bruce Cogan, Armstrong research engineer and Phase 2 contracting officer's technical representative, said the company's success would benefit Armstrong and NASA. "They are providing us with a system that will allow us to take the next step, which is putting the system in an aircraft to support flight research experiments."

A pilot flying a Gippsland Airvan while wearing a Fused Reality helmet, which superimposes an in-flight simulation over what the pilot sees out the windscreen. This gives the pilot a realistic visual simulation while experiencing all the cues of an actual aircraft in flight. (NASA photo ED15-0016-19)

Aerial refueling training is one example of how this technology can be used. In flight the pilot wears a helmet permitting him or her to see the outside view via a camera feed, while the out-the-window view of the "drogue" and "aircraft" he or she is to mate with for refueling are virtual reality. (Fused Reality) The environment in the helmet is achieved through a video board and an image generator drawing from live video. Sunlight from the aircraft's windows is the framework for the virtual world, explained Edward Bachelder, STI technical director and inventor of Fused Reality. "Sensors on the aircraft add to the flight simulator. It's the motion of the aircraft that drives the simulation. We could not have developed this without NASA."

Following a successful set of ground tests, Armstrong pilots Troy Asher, Tim Williams and Jim Less flew the system from Mojave Airport using the Calspan Corporation's Learjet 25 variable stability in-flight simulator. "It is a cross between a simulator and a video game," said Asher. "It's not like anything I've seen before. You get into the familiar environment of the airplane and the goggles display virtual objects (like a tanker out the window) on top of what's really there. It's like being in a very realistic cartoon where all the acceleration and tactile cues come from the airplane." David R. Landon, STI CEO, said of Fused Reality system: "The magic is in the math, not in the hardware." That's important because every few years a customer could invest in the most modern computer, helmet mounted display and the latest version of the Fused Reality software and in about 30 minutes turn any cockpit into a simulator at a fraction of the cost of building a new simulator or upgrading a current simulator. NASA provided the support for industry to develop and commercialize it as part of NASA's mission to commercialize technology.

PRANDTL-D

Armstrong demonstrated a new method of aerodynamic control with an aircraft built with a highly twisted wing and no tail (an all-flying wing). After years of research, data collection and flight tests, Armstrong's PRANDTL-D aircraft have demonstrated control without either a rudder or drag-inducing devices in the wings. The Primary Research on AerodyNamic Design to Lower Drag, or PRANDTL-D, is a student-driven project that was introduced by former Armstrong Chief Scientist Al Bowers. The goal of the PRANDTL-D program is to gather data and test Ludwig Prandtl's 1933 theory that details a more efficient aircraft wing than currently exists. Prandtl did not posit a control benefit.

Bowers designed a wing with an alternate spanload (how the lift is distributed across the wingspan) that has a *"bell"*-shaped load distribution rather than an *"elliptical"* load distribution. The spanload had never been tried until the laboratory built and flew a prototype. Although having a 22% greater wingspan over an elliptically loaded wing (today's standard) – and without any gain in mass – the new wing should demonstrate 11 percent less induced drag. But it was what Bowers deduced the spanload offered in control that drove the experiment: elimination of adverse yaw.

In 1902, the Wrights' third season on North Carolina's windy cape, the brothers brought a new glider, different in many ways from their earlier gliders. Bigger, heavier, this one bore the fruits of hours and hours of work using their own wind tunnel with balance springs and different sample airfoils trying to find one that produced suitable lift. The airfoils they'd flown with so far, and they had been using the most reputable available, left them unhappy with the results, so they decided to conduct their own experiments. They were flying with a tail for the first time, too, but the flights were not at all satisfactory. Lift was better than before but every time one of them turned, say left, the aircraft began a left roll and then slewed right instead. Nothing they did overcame this. Frustration finally led to replacing the pair of vertical fins with a single one, hinging it at its leading edge and linking it to the cradle on which the pilot lay. Now when the pilot shifted his torso left or right to warp the wings and impart a roll to the aircraft, the tail fin (now rudder) would deflect in the same direction, forcing the aircraft to turn in the direction of the roll. It worked, producing the first coordinated turn in an aircraft in flight. On October 10, 1902, the Wright brothers solved the problem of controlled, heavier-than-air flight. At the time there was no term for the control issue they'd encountered and overcome, now known as *"adverse yaw."* They were the first to successfully accomplish controlled flight that October, making 1903 possibly a bit anticlimactic. Since the Wrights, every aircraft has had a tail and rudder or devices in the wings to induce sufficient drag on the inside wing to overcome adverse yaw.

The Prandtl 3 in flight over the Muroc Model Masters (Rosamond Dry Lake). It carries a GoPro© camera on top to record the flight for later analysis. (NASA photo ED15-0330-079)

Interns

The flight tests and data collected for PRANDTL-D demonstrated that the new spanload did not suffer adverse yaw and was able to maneuver without either a tail or any drag-inducing devices in the wing that flying wings have. The PRANDTL program became a highly sought after internship at NASA Armstrong among students across the nation. Since 2015, an average of 1,500 students applied each year for only 20 slots (PRANDTL-3c).

The data gathered by PRANDTL-D led engineers and students to develop PRANDTL-M, a concept for a Mars airplane that may collect and transmit valuable information back to Earth. The idea: Since any spacecraft going to Mars carries ballast, why not incorporate a 6U cubesat as part of the ballast in which a foldable PRANDTL-M could be ejected once the spacecraft has descended far into the atmosphere to separate. Once ejected, the small aircraft could then fly an autonomous path, collecting data, mapping terrain or even circling the descending spacecraft to give us the very first view of a vehicle landing on another planet. Armstrong continues to gather research and data on proverse yaw through the non-elliptical bell-shaped spanload distribution in the hopes of offering a new method of aircraft control and efficiency for future aeronautic use.

The very first PRANDTL-D to fly was requested by Russell Lee, chairman of the aeronautics department at the Smithsonian Institution, because of its significance in flight history. The California Science Center also requested a PRANDTL-3 that is on display.

Interns

In 2018, Abbigail Waddell leaned over bundles of wires and circuit boards to see if a system she had helped develop with other interns during two summers at Armstrong was ready for testing. Waddell, then attending North Carolina Agricultural and Technical State University studying electrical engineering, adjusted the electronic pressure measurement system and nodded it was ready. Chris Jensen, a mechanical engineering major at Embry-Riddle University in Prescott, Arizona, blew air through a large rubber tube and a gauge indicated the pressure was rising as Jensen continued to blow. They were testing a system of 89 pressure ports embedded in the wing of the PRANDTL-3c glider, whose purpose was to measure pressure at key locations on both surfaces of the aircraft's wing, mapping lift in the process.

Before the aircraft was ready for flight, however, there was more work to do. With the system validated, students crafted a box with a 3D printer for it. Deborah Jackson, an aerospace engineering student at Embry-Riddle, Prescott, Arizona, was one of the students who helped meticulously connect each of the pressure ports on the wing to transducers in the box via 89 very small rubber tubes embedded in the wing. The transducers convert the air pressure on the wing to electronic data. During the previous two summers, Jackson worked on the FOSS flown on the aircraft, which gathered data in 2017 showing strain distribution on the aircraft's wing. *"The variety of experiences that I have been able to get is the best part,"* Jackson said. *"I worked in the electrical engineering lab and now I am working as an aerospace engineering student. I have learned so many things that are going to make me a better engineer and a better individual. I can also see the bigger picture."* (PRANDTL-D interns)

Victoria Hawkins, a graduate student focusing on unmanned and autonomous systems engineering at Embry-Riddle in Daytona Beach, Florida, said, *"Doing flight research and not just writing a theoretical paper about how it will be tested is exciting, and being in charge of it, it's on me if the flight fails or not."*

NASA interns Victoria Hawkins and Macie Kowalski working on the FOSS that was carried on Prandtl-3c to map the spanload. (NASA photo AFRC2018-0188-06)

Dream Chaser SNO

Inspiring and exciting students while developing a talent pool for NASA and the aerospace industry are key to science, technology, engineering and mathematics (STEM) education. (Armstrong Interns' Blogs) *"We could give them the answers, but we give them the room to make their own discoveries and their own mistakes,"* said Robert *"Red"* Jensen, the small unmanned aircraft Systems (sUAS) chief pilot and master technician for the Dale Reed subscale Flight Research Laboratory. David Berger, Armstrong's University Affairs officer, said *"We are helping to provide opportunities for students,"* he said. It's meaningful not only as a learning experience, but also by contributing to NASA's mission.

In June 2020, the Armstrong Flight Research Center and Ames Research Center Offices of STEM Engagement (formerly Education) combined into one regional California Office of STEM Engagement (OSTEM). There are two main internship programs at these centers, one managed by OSTEM and another, Pathways, which operates under Human Resources.

The outward face of OSTEM internships has evolved through the years due to upgrades to a sleek new website, which includes information about OSTEM and Pathways internships and houses an improved applicant management system. In the face of the COVID-19 pandemic the OSTEM internship program implemented a large-scale virtual internships program.

There are three OSTEM internship sessions (fall, spring and summer) that run year-round, and interns range from high school to doctorate levels. Applicants must be 16 years or older to apply and have a minimum of a 3.0 GPA. The majority of opportunities are for U.S. citizens, but some are available to students from select international countries. For more information or to apply for opportunities, visit https://intern.nasa.gov.

Dream Chaser SNC

NASA Administrator Charles "Charlie" Bolden visited Dryden (now Armstrong) May 22, 2013 to see the Sierra Nevada Corporation's (SNC's) Dream Chaser test vehicle that arrived at the center a week earlier. Bolden, SNC's Director of Flight Operations and former NASA astronaut Steve Lindsey and Patrick Stoliker, Dryden deputy director, outlined the ground and flight tests for the Dream Chaser to news media representatives gathered in a Dryden hangar. SNC planned a set of ground tows on the Edwards main runway, as well as captive-carry and free-flight tests. *"I'm personally excited about having Dream Chaser here at Dryden,"* Bolden told the assembled news media personnel, Sierra Nevada and NASA staff. *"I can't think of a better place to be testing a vehicle like this than bringing it right out here to the Edwards dry lake bed, which is very historic in its own right,"* he added.

Dream Chaser made its first free-flight October 26, 2013. Slung beneath a Chinook helicopter, carried to 12,500 feet, and once aligned with the runway the helicopter released Dream Chaser for its first free flight. Guided by an automatic pilot, the engineering test model made a steep descent and then flared for a smooth landing on Edwards AFB's main Runway 22.

On November 17, 2017, Dream Chaser made its second free flight. Hoisted to the same altitude, this time by an Erikson Air Crane, the reusable spacecraft was released for its flight to the main runway at Edwards. The descent was perfect, as was the flare, but when the landing gear deployed the left gear did not come down. Still, the vehicle flared smoothly and touched down as expected. But once airspeed bled off enough, the left side of the craft sank, contacted the runway and rolled off the main runway. While it looked dramatic, the entire flight – including the landing – were in fact a success: When crews got to the vehicle they found the flight computers still operating and later assessment of loads indicated that had a pilot been on board he'd have fared well. It was a demonstration of the Dream Chaser's overall integrity.

The testing was part of NASA's Commercial Crew Program (CCP) initiative to develop safe, reliable and cost-effective access to and from the International Space Station and low-Earth orbit (LEO). It was one of three spacecraft developed for that role under the CCP, the others being Boeing's CST-100 capsule and a crewed version of Space Exploration Technologies' (SpaceX) Dragon capsule. The Dream Chaser is the only one designed to make an airplane-style landing on a runway, similar to landings of the now-retired space shuttles.

As SpaceX's Dragon capsule completed its first commercial astronaut delivery to the International Space Station (ISS) in 2020, SNC has focused on using Dream Chaser as a cargo delivery system to the ISS. In 2016, NASA selected Dream Chaser to fly six cargo missions to the International Space Station, and the company aims to have the first cargo delivery flight to the ISS in 2021.

Sierra Nevada Corp.'s Dream Chaser suspended in a gantry in the Flight Loads Laboratory for its Moment of Inertia swing. (NASA photo AFRC2017-0065-402)

Suborbital Flight Testing

Dream Chaser's design is based on the HL-20 — a NASA lifting body design that was itself based on a Soviet spacecraft called the BOR-4. A company called SpaceDev resurrected the design prior to being purchased by SNC in 2008.

To the Moon, Mars, and Beyond with Suborbital Flight Testing

Facilitated by NASA's Flight Opportunities program, suborbital flight tests on commercial vehicles ranging from high-altitude balloons to parabolic aircraft to rockets help advance key innovations that could be essential for lunar or Martian missions.

"These suborbital flights enable researchers to quickly and iteratively test technologies, making adjustments between flights," said John Kelly, program manager for Flight Opportunities at NASA's Armstrong Flight Research Center. *"The ultimate goal is to drastically shorten the time it takes to bring an idea from the laboratory to orbit or to the moon."*

Several technologies selected for use on vehicles supporting NASA's Commercial Lunar Payload Services (CLPS) and Human Landing Systems (HLS) initiatives have leveraged suborbital flights for testing. They offer capabilities that address challenges of safely getting to the moon and building long-term, sustainable outposts there.

Entry, descent, and landing (EDL) technologies, such as terrain relative navigation and hazard detection/avoidance, are of particular importance as NASA looks to send robotic and crewed spacecraft to the lunar surface. An auto-landing system from Astrobotic with Flight Opportunities heritage is scheduled for its first lunar voyage in 2021. NASA also selected Astrobotic to deliver the Volatiles Investigating Polar Exploration Rover (VIPER) to the moon using its Griffin lander. Griffin will employ a lidar-based hazard detection and avoidance system similar to one tested through Flight Opportunities on Masten Space Systems' Xombie vertical takeoff vertical landing rocket. That test confirmed the technology's ability to detect and avoid hazards of about 10 inches (25 centimeters) or larger for a safe landing.

UP Aerospace launching its SpaceLoft rocket from Spaceport America in New Mexico, part of the Flight Opportunities program. (NASA photo AFRC2018-0223-110)

A navigation doppler lidar technology from NASA's Langley Research Center in Hampton, Virginia, was tested in 2017 on suborbital flights. It will also fly to the moon on two early CLPS missions for testing in advance of potential use on a crewed mission under Artemis.

Finally, the lander vision system from NASA's Jet Propulsion Laboratory (JPL) in Southern California has been integrated into prospective lunar lander guidance systems as well as NASA's Mars Perseverance rover. Early flight testing on a Masten rocket helped increase its technology readiness for space missions.

In addition to the technologies flying on them, lunar landers being developed by industry have also leveraged suborbital flights for testing. For instance, Draper – one of several companies developing a lander for NASA – tested its terrain relative navigation system on a Masten flight and a high-altitude balloon flight with World View Enterprises in 2019.

Airborne Science

Masten Space System's Xodiac vertical takeoff, vertical landing rocket at the Mojave Air and Space Port. (NASA photo AFRC2018-0223-110)

The tests enabled Draper to evaluate the system's visual navigation capabilities at a range of altitudes and facilitated successful identification and tracking of more than 50 terrain features at any given time throughout the majority of the flight.

"Suborbital flights give technologists the opportunity to exceed what is possible in ground-based testing. With relatively low cost and risk, they can make improvements on an accelerated schedule and gain critical flight heritage that facilitates selection for a mission," said Kelly. *"In addition, technologies tested on these vehicles are valuable not only to NASA. Many are licensed by industry or funded for additional development."*

Airborne Science

Alongside a second C-20A, a Predator B (Ikhana), two Global Hawks and two ER-2s, the DC-8 continues to be the king platform of the Airborne Science Program because of its cabin and payload size. In January 2006, the center turned operational control of the DC-8 over to the University of North Dakota under a cooperative agreement wherein the university housed and operated the platform. The aircraft was returned to the center in August 2007, where it resumed its airborne science work.

Operation IceBridge, which ran from 2009 to 2019, monitored changes in polar ice caps during which the DC-8 participated in eight campaigns (1,530 hours), along with the C-20A. In the span of one month, the DC-8 visited the tropics, the Artic, Antarctica, South America and Greenland as part of the Atmospheric Tomography (ATom) airborne science mission. ATom studied pollution in the lower atmosphere and its effects in the creation of greenhouse gases by comparing data gathered on the missions with computer models to refine the modelling.

For six weeks in the summer of 2016, scientists from the United States and the Republic of Korea intensively studied air pollution over the Korean peninsula under Korean-U.S. Air Quality (KORUS-AQ) project. Their mission was to diagnose the complex causes of the country's poor air quality and in so doing lay the groundwork for next-generation pollution monitoring from space that both nations plan to launch in the next few years. Among the platforms used for data collection was the center's DC-8. Overall, more than three-quarters of the particulate matter measured during the study was formed by secondary chemical reactions rather than being directly emitted from smokestacks or tailpipes. (KORUS-AQ).

Marlon Espinoza on the top of the DC-8's fuselage preparing an instrument package for Operation IceBridge. (NASA photo AFRC2018-0230-12)

Airborne Science

In September 2019, the DC-8 completed a two-month investigation into the life cycles of smoke from fires in the United States. The goal was to better understand smoke's impact on weather and climate and provide information that will lead to improved air quality forecasting. Fire Influence on Regional to Global Environments Experiments – Air Quality (FIREX-AQ) targeted broad questions about the chemical and physical properties of fire smoke, how it is measured and how it changes from the moment of combustion to its dispersion hundreds or thousands of miles downwind. All of these have implications for public health. Several aircraft based in Boise, Idaho, including the DC-8 and an ER-2, worked in unison to sample smoke plumes and their changing chemistry along with weather dynamics, tracking the plumes from combustion to destinations often several states away. *"Armstrong hosted 163 scientists from 31 institutions on the mission. The DC-8 flew 158 hours on 23 data acquisition flights and engaged fires in 18 states from Washington to Florida,"* said Chris Jennison, DC-8 mission manager. The ER-2 flew 63 hours, said Brain Hobbs, ER-2 project manager. *"Missions covered eight states and included data collection over numerous wildfires in coordination with satellite overpasses."*

In mid-August, the base of operations moved to Salina, Kansas, with flights directed at smoke from agricultural fires in the U.S. southeast. There are hundreds of these fires every year and they are closely situated to population centers, but their small size relative to satellite observational capability means they often go undetected by the satellites that provide the basis for many estimates of smoke emission amounts. The aircraft observations also are critical to understanding small-scale plume dynamics and their scientific impacts. *"What's burning matters, but how it's burning matters maybe even more,"* said Carsten Warneke, University of Colorado and NOAA mission scientist for FIREX-AQ.

More recent DC-8 missions included SnowEx, a multi-year airborne snow campaign. The overarching question for SnowEx: how much water is stored in Earth's terrestrial snow-covered regions? More than one-sixth of the world's population (~1.2 billion people) relies on seasonal snowpack and glaciers for its water supply, and snowmelt-generated water is likely to decrease this century. Researchers used a combination of remote sensing and ground data to investigate the distribution of snow water equivalent (SWE) and the snow energy balance in different canopy types, densities and terrain. This campaign acquired a time-series of repeat L-band Interferometric Synthetic Aperture Radar (InSAR) data in several snow climates in California, Idaho, Utah, Colorado and New Mexico.

The DC-8 being readied for FIREX-AQ. It is festooned with sensors sprouting from various windows on the ex-airliner. The Fabrication Shop at Armstrong builds plugs that hold the sensors, which then seal the hole where the windows used to be. These can be taken out and replaced with other sensors or the windows themselves. (NASA photo AFRC2019-0101-041)

C-20A

NASA tail No. 802, Armstrong's C-20A, is an excellent example of the center's two largest missions – Aeronautic Research and Airborne Science – coming together to provide a world-class capability. Armed with an Armstrong-developed precision autopilot and a JPL-developed airborne radar, the C-20A is able to measure precise changes in multiple areas of interest such as earthquake faults, volcanoes, vegetation, water, and ice.

The C-20A is a modified Gulfstream III business jet. Back in 2005, the C-20A was stripped down and built back up as a test bed that could fly a few standalone instruments (like a smaller version of the Armstrong DC-8). After a few years of flying various instruments, the JPL's Unmanned Aerial Vehicle Synthetic Aperture Radar (UAVSAR) became available. A pylon was added to carry the 960-pound external UAVSAR pod and the Armstrong Platform Precision Autopilot (PPA) was installed. The PPA provides the capability to reliably collect UAVSAR radar images repeatedly over the same routes with remarkable precision, which is critical for a remote sensing technology called InSAR. InSAR makes it possible to accurately quantify centimeter-level changes caused by levee breaks, snow accumulation, earthquakes, volcanoes, glacier melting and landslides. (UAVSAR)

The C-20A

The C-20A has been deployed throughout the continental United States, Alaska, Hawaii and to foreign countries to include Iceland, Germany, Norway, Japan, Panama, Costa Rica, Argentina and Gabon, Africa. Deployments can range from a few days in New Orleans and on up to 35 days supporting an 11-stop campaign all over South America. In a busy year, the C-20A will deploy for nearly 75 days.

The C-20A UAVSAR imaged areas affected by Hurricane Florence in 2018. Observations covered a span of one week and were used to map flood expansion over urban and rural environments. In collaboration with NOAA, NASA researchers proposed methods to develop maps shortly after flood events to inform managers and first responders.

The UAVSAR system has also imaged the Kilauea volcano in Hawai'i. Repeated measurements were used to quantify changes in the volcano's shape between 2010 and 2011. In 2018, Kilauea had its most effusive eruption and researchers generated fine-resolution topographic maps to estimate the amount of lava that was produced. This information improves the understanding of volcano behavior and thus our ability to predict eruption events.

Armstrong's C20A with the UAVSAR pod attached to the fuselage center body. Engineers monitor data from workstations on board.(NASA photo AFRC2020-0099-08)

During a two-week campaign in 2016, NASA collaborated with the European Space Agency (ESA) on the AfriSAR mission. Researchers measured plant mass, distribution of trees, shrubs and ground cover, and diversity of plant and animal species – not only from Gabon's rainforest but also from the country's wetlands, mangrove forests and savanna – using the Armstrong-supplied C-20A and crew that carried a UAVSAR under its belly. *"We know how much carbon dioxide is being emitted into the atmosphere by fossil fuel emissions, but we don't have a good estimate of how much carbon is being taken up from the atmosphere and where it's stored,"* said Lola Fatoyinbo, a research scientist at NASA's Goddard Space Flight Center in Greenbelt, Maryland.

The Central African nation of Gabon is slightly smaller than the state of Colorado and is home to one of the most pristine rainforests on Earth. Terrestrial ecosystems play an important role in the global carbon cycle, removing 2.7 pentagrams of carbon per year (28% of atmospheric CO2 from fossil fuel emissions) and emitting 1.0 pentagrams of carbon per year as a result of land-use change. These estimates carry the largest uncertainty (30%-50%) of all carbon budget components, and there is no consensus on the location of terrestrial carbon sources and sinks. When applied to satellite data, such algorithms fill important knowledge gaps and elucidate how carbon sinks respond to climate, anthropogenic emissions, land use patterns and governmental policies.

NASA team members and Gabonese hosts pose amidst the roots of a large tree in the rainforest of Gabon during the AfriSAR mission. (NASA photo AFRC2016-0054-091)

Hurricanes

The San Andreas Fault in California is a tectonically active and landslide-prone region. The C-20A carried the UAVSAR over ruptured or continuously creeping fault traces. Not having been done before, the flights captured baseline data over this region to provide rapid earthquake response and hazard mitigation when an earthquake occurs. UAVSAR is a powerful tool in this study because the regularity of the flights provided great spatial detail on how changing environmental conditions result in changes in landslide motion. This allows scientists to study the distribution and mechanisms of shallow fault slips, which will help scientists have better predictive power of potential earthquake rupture and afterslip.

Hurricanes

Armstrong operated two first-generation Global Hawks as science platforms, flown from a specially built ground control station. An example of a science mission was NASA's Hurricane and Severe Storm Sentinel, or HS3, taking place in 2013. The mission was the first deployment for the unmanned aircraft away from its regular base of operations at Armstrong. In addition, the pilots operated the aircraft from two locations on opposite coasts. After loading specialized science equipment, the two Global Hawks flew from Edwards AFB/Armstrong in California to NASA's Wallops Flight Facility in Virginia. Flights from the U.S. East Coast take less transit time to the target than those from Armstrong and allow the aircraft to travel further out over the Atlantic and collect data for longer periods.

The Global Hawk pilots must be within line-of-sight to land the aircraft, so the pilots were deployed to Wallops to manage this from the Global Hawk Mobile Operations Facility, handing off operation of the aircraft to Armstrong after reaching an altitude of approximately 30,000 feet. Additional pilots sitting in Armstrong's Global Hawk operations center assumed responsibility for the aircraft's operation until the mission was completed, when the landing operation transferred back to Wallops.

When flying in oceanic airspace, Global Hawk pilots talk with international controllers via telephone. This communication is vital as air traffic controllers provide information on altitude and number of other aircraft sharing the same domestic national airspace system as well as international airspace with the aircraft in operation. Once the Global Hawk reached an altitude of between 60,000 and 65,000 feet there were very few aircraft competing for space.

Although the flight path of the Global Hawk was preprogrammed into the aircraft's flight control computers, pilots are able to override the flight plan to accommodate scientists' requests using an alpha-numeric keypad. All Global Hawk pilots are rated to fly manned aircraft. The pilots commented that it is possible to become so engaged during a Global Hawk flight that it seems like flying a manned aircraft even though much of the sensory information available to pilots of manned aircraft is missing for the unmanned aircraft pilots. It is not possible to smell the fuel, see the weather and terrain, hear the engine starting or feel the movement from a ground control center. Although the pilots' tools are a mouse, keyboard and computer displays, the NASA Global Hawk pilots find their work challenging.

One of Armstrong's Global Hawks in flight over the Antelope Valley. The center acquired two Block 10 aircraft after the Air Force no longer needed them. They were configured as high-altitude, long-endurance science platforms. (NASA photo ED09-0306-050)

ER-2

In 2018, Hurricane Florence's storm surge and heavy inland rainfall affected coastal barrier islands and produced widespread riverine and flash flooding, which is challenging to observe through optical remote sensing due to extensive cloud cover, and at publicly available synthetic aperture radar (SAR) wavelengths due to widespread vegetation. (Global Hawk) This is particularly important at the urban-suburban interface where vegetation may obscure affects felt in these communities. The UAVSAR imagery provides a unique opportunity to map actual floodwater extent to provide validation of these physical models; opportunities to improve the same; and new data sets of complex terrain and vegetation, where flood monitoring from SAR needs continuous improvement and near real-time and/or reduced latency use of the imagery to support disaster response and recovery.

ER-2

NASA's high-altitude ER-2 aircraft completed a series of validation flights in support of the Earth-observing NASA/NOAA Suomi National Polar-orbiting Partnership (NPP) satellite. The campaign, jointly sponsored by NASA and NOAA, and based out of Keflavik, Iceland, began science flights in March 2015. The mission helped characterize Suomi NPP's various instruments. (cockpit view, ER-2) The mission also sought to improve geophysical parameter retrieval performance for such challenging polar atmospheres as well as provide anchor points for future numerical weather prediction (NWP) data assimilation studies using satellite data. ER-2 calibration flights were timed to fly directly under the path of Suomi NPP.

SOFIA

NASA, in partnership with the German Aerospace Center (DLR) (Deutsches Zentrum für Luft-und Raumfahrt), developed the Stratospheric Observatory for Infrared Astronomy, or SOFIA, as a world-class airborne observatory that complements the Hubble, Spitzer, Herschel and James Webb space telescopes as well as major Earth-bound telescopes. A heavily modified Boeing 747SP, SOFIA features a German-built 100-inch (2.5 meter) diameter far-infrared telescope weighing 20 tons, mounted in the rear fuselage. The observatory was declared fully operational in 2014 but had already been making discoveries while completing its instrument and telescope testing. (SOFIA)

SOFIA's reflecting telescope provides astronomers access to the visible, infrared and sub-millimeter spectrum, with optimized performance in the mid-infrared to sub-millimeter range. It continues the legacy of planetary scientist Dr. Gerard Kuiper, which began in 1966 with a 12-inch telescope aimed out a window of a converted Convair 990 jetliner. His work led to the development of NASA's Kuiper Airborne Observatory, a modified C-141 aircraft incorporating a 36-inch reflecting telescope that flew from 1974 to 1995.

One of the center's two Lockheed ER-2 science platforms in the hangar at Building 703. The two modular wing pods hold instruments, allowing for reconfiguration after a landing. There is also a large bay behind the pilot that carries scientific instruments. (NASA photo AFRC2016-0035-151)

Sofia

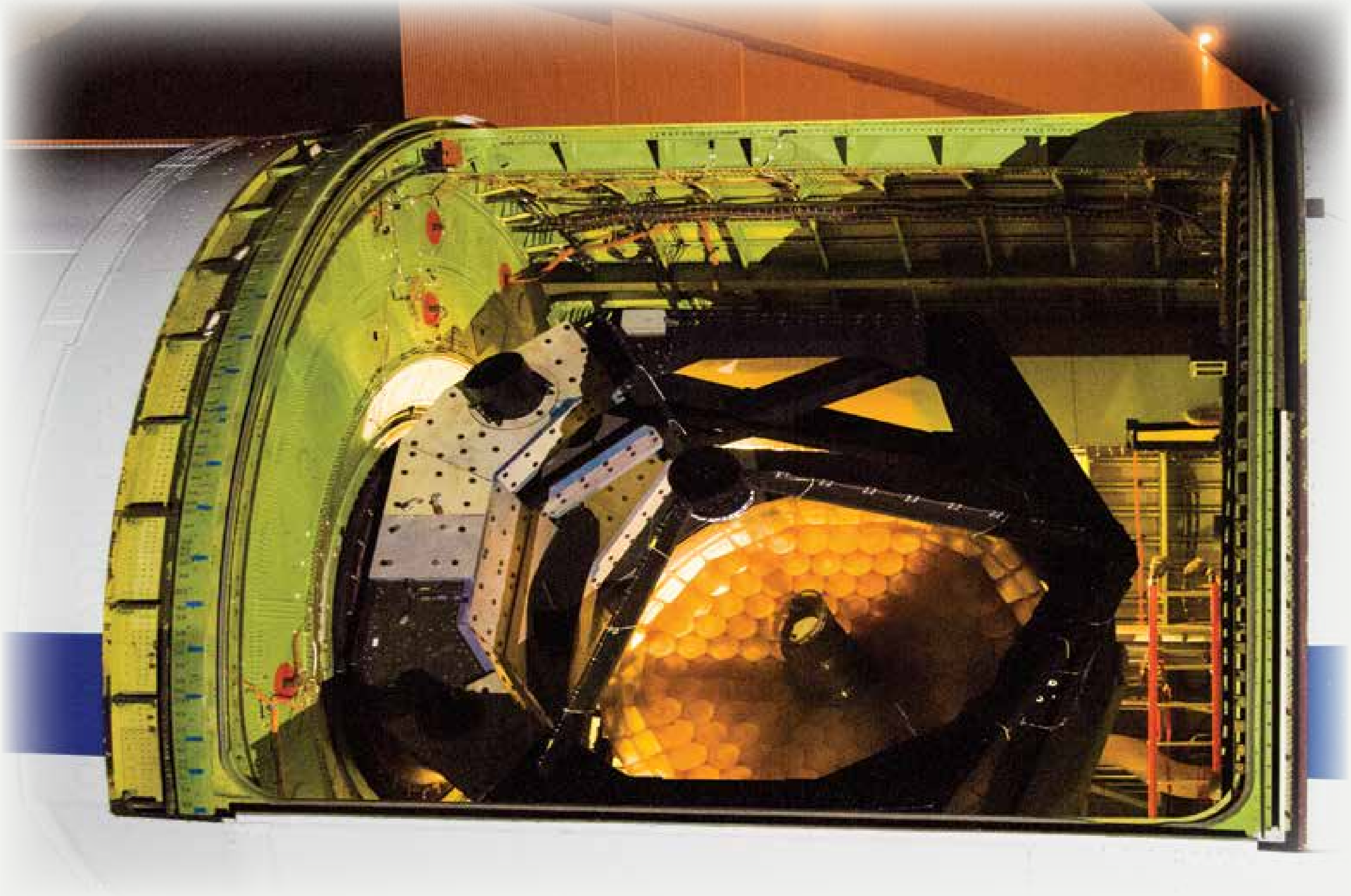
As the world's largest airborne astronomical observatory, SOFIA provides three times better image quality and vastly increased observational sensitivity than before. From its base at Armstrong, SOFIA missions are conducted over virtually the entire globe. Missions are flown at altitudes of 39,000 to 45,000 feet, above 99 % of the water vapor in the lower atmosphere that restrict the capabilities of ground-based observatories over most of the infrared and sub-millimeter spectral range. The 747SP is configured for a crew of between 15 to 20, not counting teachers and special guests, with the telescope and associated instruments taking up the back one third of the fuselage.

NASA
DLR
N747NA

NASA's SOFIA with the telescope bay open. The Stratospheric Observatory for Infrared Astronomy is nearly a 30 meter (10 foot) German telescope, which the Boeing 747SP carries (along with a crew of scientists, technicians and teachers) above 90 percent of the Earth's water vapor, providing it with a clearer view of celestial objects, and mobility nearly anywhere on Earth. This is in contrast to ground-based telescopes that cannot be moved and cannot avoid the atmospheric moisture. (NASA photo ED08-0067-28)

"An advantage of infrared is that it 'peers' through the dust that's out in space. There's a lot of dust in space between stars. The view that we get of the universe in the optical or ultraviolet wavelength is biased by dust. SOFIA probes right through that dust," said Eric Becklin, senior science advisor to SOFIA. *"In the visible and ultraviolet, you're mainly looking at stars. When you look in infrared you see stars, but also see (more clearly) the dust and the gas that those stars formed from or are throwing off as they die,"* he said.

Mobility is central to SOFIA's value. Unlike land-based or even space-based telescopes that are essentially locked in place, SOFIA can move to virtually anywhere in the world to view different things at specific times. An occultation, for example, is an astronomical phenomenon observed when a planet or moon passes across the line of sight to another celestial body. An eclipse of the sun is an occultation. Astronomers use the occulted object to make observations that can't be made under other conditions. SOFIA was in the right spot over the Pacific Ocean for Pluto's occultation in 2015, for example. The telescope captured a bright spike of light in the middle of the shadow cast by Pluto as the star's light briefly lit up the dwarf planet's entire atmosphere, providing detailed information about Pluto's atmosphere.



SOFIA's telescope and supporting structure. (NASA photo ED08-0067-10)

Model Laboratory

As part of its overall mission, SOFIA incorporates an educational and public outreach emphasis to help improve American education in science, technology, engineering and mathematics. SOFIA was designed to give elementary, secondary and college-level educators from across the U.S. hands-on participation in cutting-edge scientific and astronomical research. SOFIA's Airborne Astronomy Ambassadors fly aboard the aircraft on science missions, learning not only how the work is done, but are able to take the experience and results back to their students.

Among the flying telescope's discoveries are:

-magnetic fields in the Cygnus A galaxy are feeding material into the galaxy's central black hole. SOFIA revealed that the invisible forces are trapping material close to the center of the galaxy, close enough to be devoured by the black hole. Magnetic fields in other galaxies, such as the Milky Way, may be preventing black holes from consuming such material.

-finding the first type of molecule to form in the universe, helium hydride. Formed about 100,000 years after the Big Bang it was the first step in the cosmic evolution that Earth is part of. Helium hydride should be present in the universe but had never been detected before.

-Rather than obliterating entirely, SOFIA discovered that a supernova explosion can produce a substantial amount of the material from which planets like Earth can form. Infrared observations of a cloud produced by a supernova 10,000 years ago contains enough dust to make 7,000 Earths.

Model Laboratory

The Dale Reed Subscale Flight Research Laboratory is NASA Armstrong's one-stop-shop for small unmanned aircraft systems (sUAS) flying projects. Mainly used as a technology incubator, many projects use the model lab to fast track a flying vehicle. Full design, construction, integration and operation available in one department allows projects to begin gathering crucial flight data quickly with a greatly reduced resource expenditure. In-house capabilities include aero design, computer numerical control (CNC) and light manual machining, laser cutting, water jet, 3D printing, composite construction and mold-making as well as PC board construction and population. (Model Lab)

The lab operates a fleet of generic and program-specific aircraft ranging in size from a 13 inch span all-composite Mars exploration prototype to a 300 pound, 60% scale Super Cub powered by a turboprop burning Jet-A fuel. Research can be conducted on an existing platform, or if necessary, a new platform can be acquired and modified. In some cases, a completely new one-of-a-kind vehicle can be designed and built from scratch.

An example of the latter is the PRANDTL series of aircraft. Armstrong Chief Scientist Al Bowers designed a wing with an alternate spanload (how the lift is distributed across a wingspan) based largely on one published by Ludwig PRANDTL in 1933. Despite its introduction in a paper, the spanload had never been tried until the lab built and flew a prototype. The new spanload promises an 11.5% improvement in aerodynamic efficiency. But it was what Bowers deduced the spanload offered in control that drove the experiment: elimination of adverse yaw.

(l-r) Robert "Red" Jensen and Justin Hall run up the turboprop on the sUAS Model Lab's 60% scale Super Cub on Rogers Dry Lake. Among its uses was flying as a surrogate "intruder' during NASA's UAS-NAS program to trigger a see-and-avoid response from the prime test bed. (NASA photo AFRC2018-0011-023)

Model Laboratory

An offshoot of that project was the development of PRANDTL-M (Mars), a diminutive glider designed to fly in the Martian atmosphere, where it could gather mapping or other data. PRANDTL-M is designed to be carried in a 6-U CubeSat (a 1U CubeSat measures 10cm^3) and carried as part of the ballast on a Mars mission. NASA's Curiosity rover module carried 25 kilograms (55 pounds) of tungsten ballast for spin stablization in route to Mars. Once in its atmosphere the ballast is ejected.

Other lab tests include APV-3, a gas engine powered UAS whose wing trailing edge was extensively modified to have 44 separate control surfaces, looking not unlike a piano keyboard, as well as FOSS on the wing. Sensing a strain from a gust of wind, the FOSS directed which and how many control surfaces to deflect, and whether up or down to alleviate the gust load on the aircraft. The experiment had as its objective investigating a gust load alleviation system for full-scale aircraft.

The lab designed and built a prototype, twin-fuselage towed glider that could lead to rockets being launched from a pilotless glider at high altitudes – an approach that could significantly reduce cost and improve efficiency of sending small satellites into space. The one-third-scale twin fuselage towed glider's first flight came in 2014. The Towed Glider Air-Launch System (TGALS) is a small payload rocket-launching concept. Armstrong researchers, led by center engineer Gerald Budd who conceived the idea, developed the system. The TGALS demonstration's goal is to provide proof-of-concept of a towed, airborne launch platform. The 27-foot-wingspan glider was towed behind the DROID and released (then flown by another Lab pilot) in the demonstration phase.

The state of the art among existing air-launch platforms is a carry efficiency of approximately 0.7 (7 tenths of the aircraft's weight). The TGALS can carry twice its own weight, for an efficiency of 2.0. The rationale of a towed glider launch platform can be boiled down to this: How many babies can you carry a quarter mile in your arms, versus how many babies can you pull a quarter mile if they ride in a wagon? Potential benefits from TGALS are many. In terms of performance, the towed glider can potentially carry twice the load to altitude as the same size direct-carry conventional rocket. The concept's versatility lies in the system's ability to launch the glider from anywhere on Earth, allowing for high inclination orbits or to avoid weather patterns that ground other rockets. Placing the rocket under a glider instead of a manned aircraft reduces risks and increases load capability (the glider has no engines, fuel or human life support equipment to add to the mass).

Auto GCAS

Automatic Ground Collision Avoidance System (Auto GCAS) research began in the mid-1980s with Lockheed Martin, the U.S. Air Force and the Swedish Air Force as partners. In 2012, Armstrong partnered with the Office of the Undersecretary for Personnel and Readiness, the Air Force Research Laboratory (AFRL), the Air Force Test Center (AFTC) and Lockheed Martin to improve the existing technology. The objective was to eliminate Controlled Flight Into Terrain (CFIT), the number one killer of military pilots and the second most common cause of death among general aviation pilots. Cockpit-warning systems have all but eliminated CFIT for large commercial air carriers. CFIT happens when a healthy pilot in a perfectly good aircraft flies into the ground or raised terrain. This happens for several reasons, including loss of situational awareness and loss of consciousness due to aggressive maneuvering. Coupling software with proximity warning technology was the initial solution, but fighter pilots objected to the results as they found the program took control from them too early at critical points in a mission.

Expanding on previous work, researchers at Armstrong developed an improved ground collision avoidance system offering higher fidelity terrain mapping (created via the shuttle), enhanced vehicle performance modeling, multidirectional avoidance techniques, more efficient data-handling methods and user-friendly warning systems.

The team conducted more than 556 test maneuvers during 49 flights, some of which involved diving at the ground and flying directly at mountain sides. The flights focused on identifying any instances where Auto GCAS might impede a pilot's performance on standard tactical missions. As the airplane approached the ground, the computer sensed its velocity and location, determined how much time remained before impact, then triggered an autopilot-commanded maneuver (informed of the terrain by a database) at the last possible moment to avoid a crash – and only if the pilot did not recover in time. *"We conducted a risk reduction program under AFRL, then the work and the jet moved down the street to the Air Force Test Center, where final production integration was accomplished,"* said NASA Principal Investigator Mark Skoog.

Auto GCAS

Researchers quickly found that when fully developed and matured, miniaturized Auto GCAS technology had numerous potential civil and military applications for both crewed and remotely piloted aircraft. In 2012, the project at Armstrong adapted Auto GCAS to a small, unmanned research aircraft, a Dryden Remotely Operated Integrated Drone (DROID) and installed a smartphone application using the Android operating system linked to the aircraft's Piccolo© autopilot. Throughout the tests the smartphone-assisted autopilot repeatedly executed pull-ups or sharp turns at key moments to avoid impact with terrain in the DROID's flight path.

Armstrong team members prepare DROID 3 for an Auto GCAS test. The "bread truck" serves as a mobile ground control station (GCS) as well as a means to carry the DROID to and from the test site. (NASA photo ED12-0071-50)

At the heart of the system's design is modular software, allowing the *"take command"* aspect to remain intact while substituting different aircraft types and performances. This made it possible to transfer the technology from an F-16 to a small UAV at the center and test the same system.

In 2013, Air Force officials announced that an operational Auto GCAS system would be installed in its F-16 fleet. The Air Force and Lockheed Martin then moved to develop similar systems for use in the F-22 and F-35. NASA has also migrated the Auto GCAS to general aviation aircraft such as Langley Research Center's single-engine, Langley's composite Lancair Columbia 300 test platform.

Further development of the technology continues at Armstrong as part of the Resilient Autonomy effort, a joint collaboration with the FAA, the Office of the Secretary of Defense, and numerous Department of Defense services and Ccommands. The Armstrong team is developing the Expandable Variable Autonomy Architecture (EVAA) system, which will determine when safety should take priority over a mission and when human safety should take priority over the vehicle itself by following a set of programmed rules. The goal is to have EVAA serve as a *"moral"* compass for unmanned aircraft vehicles in much the same way that Auto GCAS performs in manned planes. *"Our goal is to build a certification approach, based on the framework of our EVAA system, for general aviation aircraft and full autonomous aircraft to be equipped with an automatic air and ground collision avoidance system,"* said Mark Skoog, Principal Investigator.

In 2018, the Auto GCAS project won the Robert J. Collier Trophy, one of the highest awards in aviation, which the NACA and NASA have won 21 times since 1915. To date (late 2020) Auto GCAS has saved 10 pilots' lives in F-16s.

ACTE

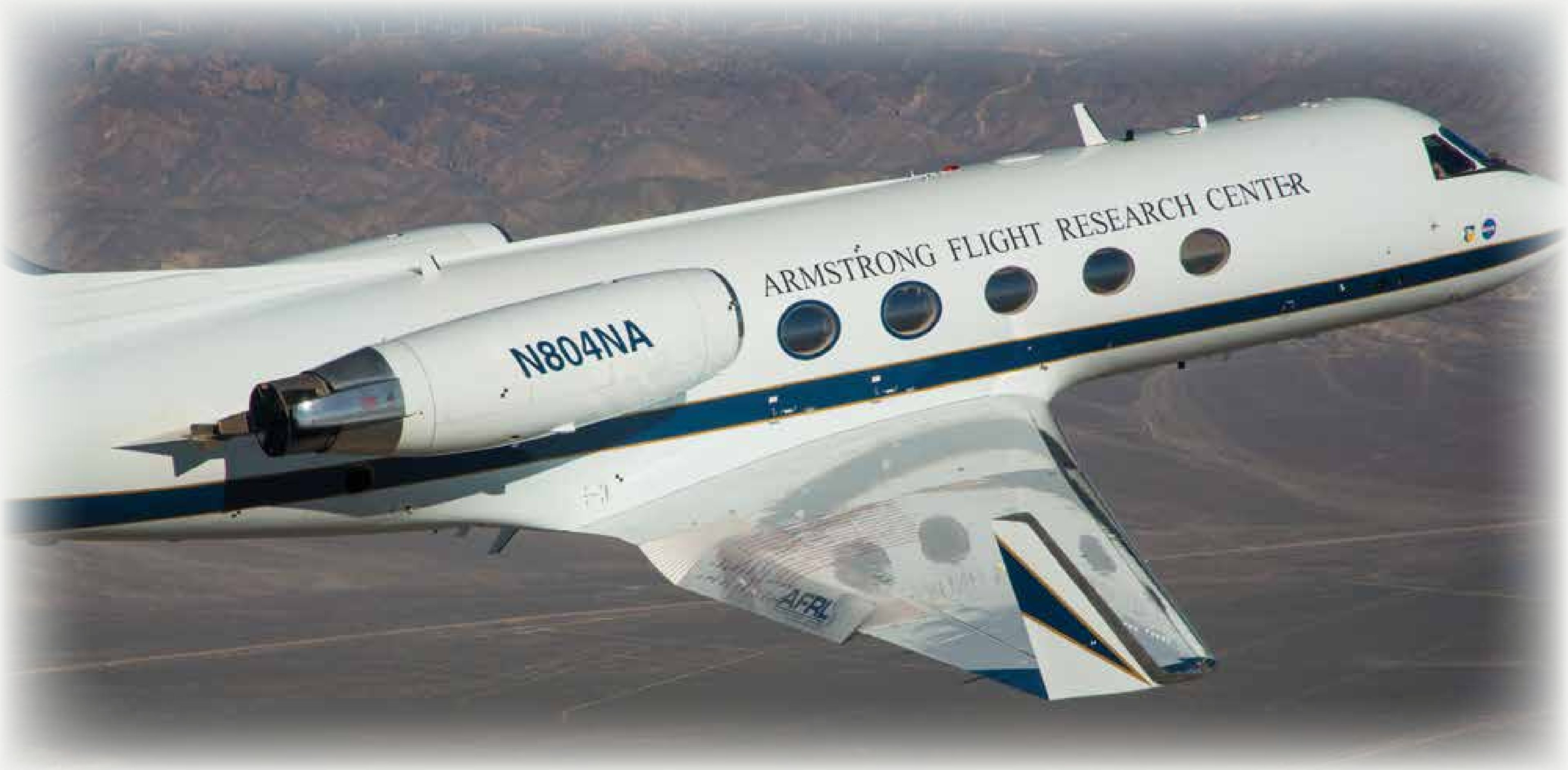
In 2014 NASA and the U.S. Air Force Research Laboratory joined forces to explore a flexible trailing edge wing flap's ability to lower airport noise and improve aerodynamic efficiency. Extending flaps for takeoff and landing and even landing gear creates considerable noise as well as drag. The testbed was a NASA Gulfstream GIII business jet (the Subsonic Research Aircraft Testbed, or SCRAT).

ACTE

Under the Active Compliant Trailing Edge (ACTE) project, the aircraft's 19-foot aluminum flaps were replaced by composite flaps with flexible material sealing the gaps at the root and outboard flap sections (picture the feathers on a bird's horizontal tail). Not only is the extended flap quieter, it is more aerodynamic because it seals the gap at both ends of the flap. The flap is built by FlexSys Inc. of Ann Arbor, Michigan. *"This flight test is one of the NASA Environmentally Responsible Aviation (ERA) project's eight large-scale integrated technology demonstrations to show design improvements in drag, weight, noise, emission and fuel reductions,"* said Fay Collier, ERA project manager at NASA's Langley Research Center in Hampton, Virginia. *"We expect this technology to make future aircraft lighter, more efficient and quieter. It also has the potential to save hundreds of millions of dollars annually in fuel costs,"* said Thomas Rigney, ACTE project manager at Armstrong.

In addition to lowering the flaps for landing tests, engineers twisted the flaps in opposite directions in flight, one end going down, with the other going up. *"We're twisting the inboard and outboard sides of the flaps in order to show that we can move the center of lift inboard or outboard,"* explains Armstrong SCRAT Chief Engineer Ethan Baumann. *"You can use a technique like this for gust load alleviation. Wing structure is designed for a worst-case gust loading condition, so if you can quickly change the curve of your wing and respond to a gust, then you can theoretically get away with designing lighter wings."*

A follow-on project involved modifying the landing gear doors of the GIII to measure noise reduction when compared to a stock GIII. Doing this involved setting up an array of 185 microphones on Rogers Dry Lake, flying a baseline with an unmodified GIII and then with the SCRAT airframe. Model testing of this fairing confirmed predictions based on previous computer simulations that this technology would result in reduced noise levels. In addition to the noise-reducing technology being integrated into manufactured aircraft in coming years, Armstrong's Kevin Weinert said it may be applicable to different classes and sizes of aircraft. *"I can see this being something integrated into aviation within the next 10 years, as reducing noise for communities around airports is a goal of aircraft manufacturers. I see this technology being applicable to other classes of aircraft as well, the biggest interest being full-size transport aircraft – commercial airliners."*



Armstrong's Gulfstream GIII "SCRAT" with the FlexSys flap deployed. From this angle, one can see the gap seal at either end of the flap, reducing drag and noise. (NASA photo ED15-0076-03)

COVID-19

With the emergence of the pandemic caused by COVID-19, Armstrong all-but closed its doors to personnel, who were sent home to telework for safety reasons. Only absolutely essential personnel were allowed on site. The response was remarkable, with many employees finding they got more work done than usual without the daily exchanges that inevitably took place on center. To be sure, the self-isolation came at an expense, as those very same exchanges are fruitful in subtle ways. Initially, management supported telework in concept but was skeptical at the idea that most of the center's work could be accomplished remotely. That attitude flipped as time passed: leadership came over hard on the side of working remotely after seeing how much was getting done. As the dust settled, center leadership went to great lengths to research, then establish new processes and protocols for when work warranted personnel being on center. The point was to minimize large groups of employees in the same building at the same time. Those performing touch labor were the first allowed back on site.

Covid-19

Michael Buttigieg watches as a member of the Antelope Valley Hospital tries on the hood he designed for COVID-19 patients. (NASA photo AFRC2020-0058-032)

In anticipation of the return to work on site, the center ensured adequate personal protective equipment (PPE) and cleaning and sanitizing supplies were available. There was also adequate COVID-19 testing capability available before greater on site work resumed. Supervisors were asked to survey work areas before their employees arrived to confirm PPE availability and ensure that social distancing criteria were met. *"Employee health is the center's top priority and the guiding principle for planning our return to the center is having employees continue to telework as much as possible,"* Glenn Graham, Director for Safety and Mission Assurance, said. *"This is to ensure social distancing and to minimize close contact between employees."*

One of the means to combat the isolation and maintain professional interaction was the use of Microsoft Teams©, a program that allowed large groups of individuals to be on the same video conference call simultaneously. This meant entire organizations could participate in the same meeting using a secure system. The center continued to fly certain missions and operate aircraft, although only those missions deemed essential, usually involving a long lead time and sometimes with an outside partner. Armstrong also flew support missions for the agency in this period.

In 2020, Armstrong joined a local public-private task force with a hospital, a college, the City of Lancaster and two spaceflight companies and ended up patenting an improvement to an oxygen helmet for COVID-19 patients. A team led by Armstrong engineer Michael Buttigieg was charged with developing a low-cost, easily made assisted breathing helmet that could withstand pressures that off-the-shelf units weren't designed for, without affecting the supply chain. *"NASA is more than scientists, engineers and explorers. We are neighbors and members of communities across the country,"* said NASA Administrator Jim Bridenstine. *"In a time like this, it's critical that we contribute the vast expertise of our workforce to do all we can to help our neighbors, our communities and the nation."* The task force worked closely with medical professionals at the hospital to provide alternative solutions to needed equipment that is not available for a large-scale emergency. Oxygen helmet manufacturers have been unable to meet the surge in demand in response to COVID-19, which often deprives patients of oxygen.

One of its first efforts, building a prototype oxygen hood, has shown benefits. The production of 500 copies began at The Spaceship Company's Faith Facility in Mojave, California. The device is an oxygen hood for COVID-19 patients exhibiting minor symptoms, minimizing the need for those patients to use ventilators. The device functions like a continuous positive airway pressure (CPAP) machine to force oxygen into a patient's low-functioning lungs. (Oxygen Hood) *"We looked across our center's expertise in innovation, engineering, design and fabrication of unique systems to bring NASA knowledge and people together to collaborate on solving the needs and challenges brought about by the COVID-19 situation,"* said Armstrong Chief Technologist David Voracek.

"The patient will be located inside this canopy where aerosol viral contaminants will be vacuumed out through a viral filter located within the canopy," said Allen Parker. *"In doing so, the health provider can freely work around the patient outside the canopy with minimal risk."* The ingenuity and teamwork displayed by NASA employees, along with their task force partners while in quarantine, may help in preparing for future emergencies that affect the nation.

BOSCO and AirBOS

In 2015, NASA's goal of developing a quiet supersonic aircraft came another step closer following a pair of successful first flights in a series demonstrating patent-pending Background Oriented Schlieren using Celestial Objects (BOSCO) technology, which uses the sun as a background to capture unique, measurable images of shockwaves. Improved image-processing technology made it possible to capture hundreds of observations of each shockwave, benefiting engineers in their efforts to develop a supersonic aircraft that will produce a soft *"thump"* in place of a disruptive sonic boom.

Schlieren photography is a technique that makes invisible flow features visible: it can capture pressure waves flowing off an object. When light travels through different densities, it bends. This method can be applied to imaging wing vortex locations and relative strengths important for Armstrong's research into improved efficiency for subsonic aircraft.

Although the photographic method has been in use for over a century, recent research by NASA enabled its application in flight and greatly enhanced the detail of the images. NASA-improved schlieren captured the visual data of shockwaves produced by a U.S. Air Force Test Pilot School T-38 aircraft traveling supersonically. The filter, known as a hydrogen-alpha solar filter, was installed in one of three modified high-speed cameras positioned strategically on the ground, allowing visually fine details of the sun to observe air density changes, making the details clearer, explained BOSCO Principal Investigator Michael Hill. *"As the light rays pass through the flow around the airplane the different air density caused by the flow bends the light, which allows us to see the texture of the sun's surface move on the digital image."* Engineers could then calculate how far each *"speckle"* on the sun moved. (BOSCO in action)

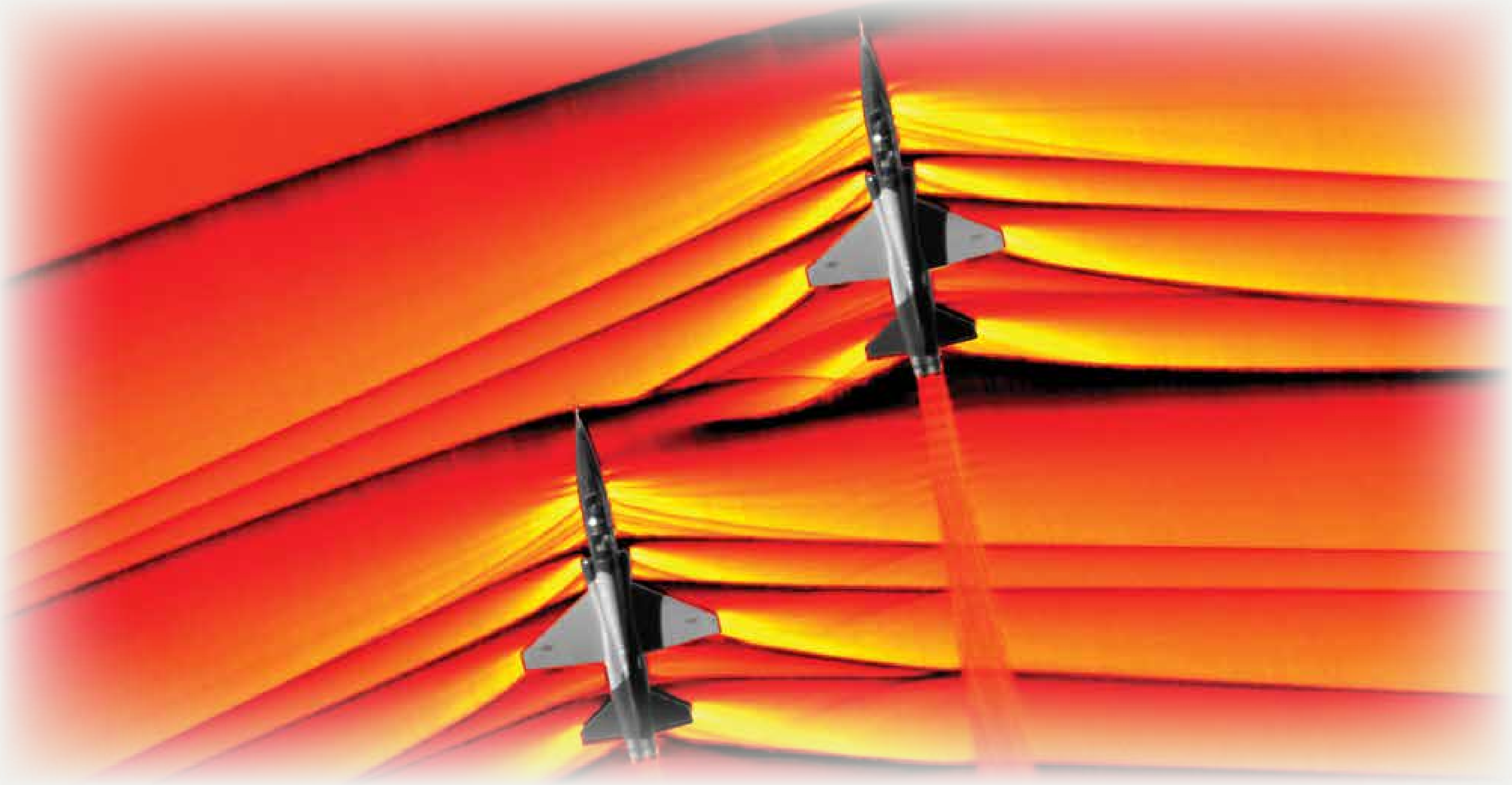
"The amount that the speckle moves is proportional to the strength of the density gradient," said Edward Haering. *"Shockwaves and vortices have strong density gradients so these flow features become visible in background oriented Schlieren photography. The photographs easily show where these features are. A more difficult problem we hope to solve is to extract the quantitative density gradients from these images."*

The overall goal of the Schlieren research is to develop a method to image the shockwaves propagating from the bottom of the aircraft toward the ground. Visualizing these complex shockwaves produced by a supersonic aircraft allows NASA researchers to validate design tools used to develop the proposed Quiet Supersonic Technology (QueSST) research aircraft. QueSST will be the first aircraft to demonstrate supersonic flight with the soft sonic *"thump,"* and could unlock the future to commercial supersonic flight over land.

Paul Bean and Paul Dees in a down moment during the BOSCO flight, ready to capture the Schlieren image as the T-38 flies between them and the sun. (NASA photo AFRC2016-0093-007)

Bosco and AirBos

Shockwaves produced by aircraft merge together as they travel through the atmosphere and are responsible for what is heard on the ground as a sonic boom. The images feature a pair of T-38s from the U.S. Air Force Test Pilot School at Edwards AFB, flying in formation at supersonic speeds. The aircraft were approximately 30 feet apart, with the trailing aircraft flying about 10 feet lower than the leading T-38. The shockwaves appear with exceptional clarity, the flow of the shockwaves from both aircraft is seen, and for the first time, the interaction of the shocks can be seen in flight. *"If you look at the rear T-38, you see these shocks kind of interact in a curve,"* said Neal Smith, a research engineer with AerospaceComputing Inc. at Ames' Fluid Mechanics Laboratory. *"This is because the trailing T-38 is flying in the wake of the leading aircraft, so the shocks are going to be shaped differently. This data is really going to help us advance our understanding of how these shocks interact." "We're seeing a level of physical detail here that I don't think anybody has ever seen before,"* said Dan Banks, senior research engineer at NASA Armstrong. The images were captured from the center's B200 King Air using an upgraded camera system to increase image quality.



Two USAF test pilot school T-38s going supersonic and captured by BOSCO technology. (NASA photo AFRC2016-0093-007)

In addition to avionics upgrade for the King Air camera platform, which improved the ability of the aircraft to be in exactly the right place at precisely the right time, the team also developed a new installation system for the cameras, drastically reducing the time it took to integrate them with the aircraft. *"With previous iterations of AirBOS, it took up to a week or more to integrate the camera system onto the aircraft and get it working. This time we were able to get it in and functioning within a day,"* said Tiffany Titus, flight operations engineer on the King Airs. Obtaining the images required a great deal of skill and coordination from engineers, mission controllers, and pilots from both NASA and Edwards' U.S. Air Force Test Pilot School. In order to capture these images, the King Air, flying a pattern about 30,000 feet, had to arrive in a precise position as the pair of T-38s passed at supersonic speeds approximately 2,000 feet below. AirBOS was flown as a sub project under NASA's Commercial Supersonic Technology (CST) project.

SonicBAT and QSF18

Armstrong sent a team of researchers, information specialists, pilots and mechanics to the Kennedy Space Center in 2017 for a two-week campaign, the second series of Sonic Booms in Atmospheric Turbulence flights, or SonicBAT, a continuation of 2016's successful supersonic research WSPR flights flown at Edwards Air Force Base. The Waveforms and Sonic boom Perception and Response project, or WSPR, took place in 2011 at Edwards AFB, where sonic booms are relatively common. The 100 volunteer residents of Edwards used a questionnaire to provide feedback on low-amplitude *"thumps"* created with the F/A-18 quiet-dive maneuver. (SonicBAT)

SonicBAT helped NASA researchers better understand how low-altitude atmospheric turbulence affects sonic booms. Per Ed Haering, SonicBAT Principal Investigator at Armstrong: *"Turbulence can make sonic booms quieter, or it can make them louder. Last summer we tested in the hot, dry climate of Edwards AFB. We know that humidity can make sonic booms louder, so we need to test some place wetter and Kennedy fits that bill."* The team collected sonic boom signature data using audio equipment to capture noise levels both above and below the turbulence layer, providing a comparison both before and after the boom traveled through atmospheric turbulence. To do this, a NASA Armstrong F-18 took off from Kennedy's Shuttle Landing Facility and flew off the coast of Cape Canaveral at an altitude of 32,000 feet and began a designated flight path: it exceeded Mach 1 during the dive.

SonicBAT and QSF18

Meanwhile, a pilot flew the Center's TG-14 motor glider equipped with a wingtip microphone at altitudes between 4,000 to 10,000 feet, above the low-altitude turbulence layer. At the test point, the TG-14 temporarily shut down its motor and glided, ensuring the wingtip microphone picked up a clean, accurate sonic boom signature before it traveled through turbulence. To collect signatures of sonic booms that travel through the turbulence there were two microphone arrays on the ground at the Kennedy Space Center, each with 16 microphones to collect data. The project collected data in three different conditions, including low turbulence, medium turbulence and significant turbulence, to obtain a stronger understanding of how the variations affect sonic booms.

In 2018, following months of preparation, including legislative engagement and environmental assessment, Armstrong sent another diverse team to Houston and Galveston to support a second booming campaign. It completed a series of quiet supersonic research flights off the coast of Texas, near Galveston, looking to measure the community's response to a unique acoustic experience.

Paul Dees sets up monitoring tools to capture sonic booms over Edwards Air Force Base during the SonicBAT 1 project, conducted at Edwards.(NASA photo AFRC2016-0195-094)

An aircraft flying at supersonic speeds currently produces a sonic boom so loud that commercial supersonic flight is prohibited over land. However, NASA pilots flew an F/A-18 supersonic research aircraft in a unique maneuver, creating a quieter sound more closely resembling a thump than a traditional sonic boom. The F/A-18 started in an oval flight pattern offshore, then dove from approximately 49,000 feet altitude and briefly went supersonic before recovering to level flight at approximately 30,000 feet altitude. This type of dive produces a sonic boom that is perceived in a specific area as a quieter *"thump"* similar to the predicted sound signature of the low-boom flight demonstrator (LBFD). This was the noise the community was asked to evaluate via surveys. Community feedback data were gathered through the use of a survey from which 500 residents were recruited as volunteers. If they heard the thumps, they were asked to define the level at which they were able to perceive the sound. Quiet Supersonic Flights 2018 (QSF18) data are used to help NASA better understand successful data collection methods for future flights using the X-59 QueSST.

Two F/A-18 aircraft from Armstrong were used for the QSF18 flight campaign, allowing flight crews to switch and fly as many as three flights in a day. The team completed 52 sonic thumps over the course of 22 mission flights and survey participant response was high, with their reactions aligning with researchers' expectations. *"This is the first time in decades that we have reached out to a large community as part of our supersonic research. We've measured the noise levels and the impact on structures, as well as surveyed people for annoyance, to make certain that these tests were safe and well planned. QSF18 was a big step in NASA's efforts to understand what is required for acceptable supersonic overland flight,"* said Peter Coen, Commercial Supersonic Technology Project Manager.

Starting in the early 2020s the X-59 will fly directly over yet-to-be-selected communities to collect data using lessons learned from QSF18. "Galveston is both honored and excited to be part of this project," said Galveston Mayor James Yarbrough. NASA also engaged teachers and youth of the Galveston area through STEM learning activities. Those activities featured two web-based opportunities, including a "Seeing Sound" learning module with classroom activities for students, and a citizen scientist activity for anyone in the Galveston area to submit data on the sounds they heard. QSF18 is an element of NASA's Commercial Supersonic Technology project.

The X-48

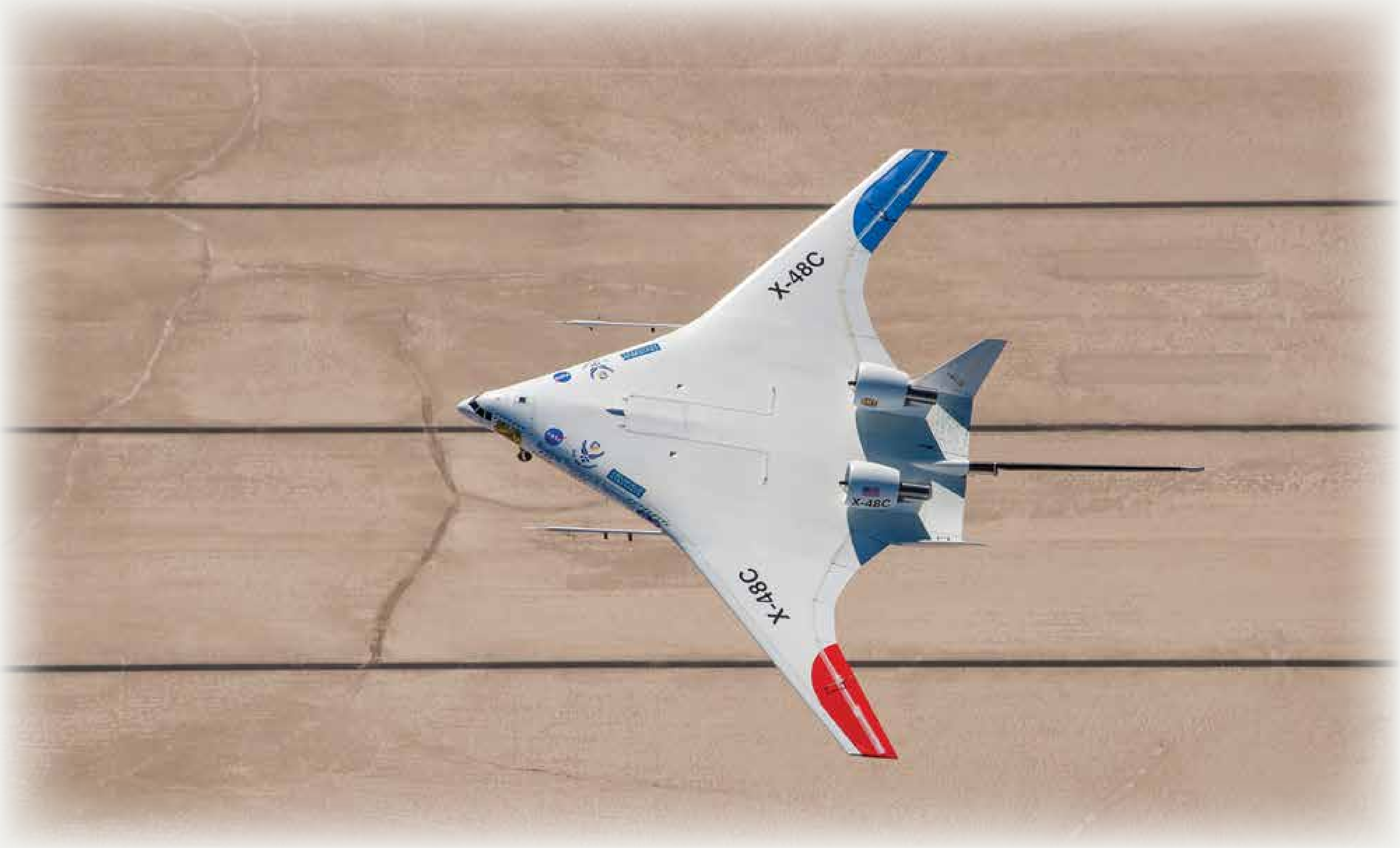
In 2012, Boeing Phantom Works, NASA and the Air Force Research Laboratory joined to study the structural, aerodynamic and operational advantages of the blended wing body (BWB) concept, a cross between a conventional aircraft and a flying wing design. A BWB blends the *"fuselage"* into the wings with a seamless transition. A follow-on upgraded, modified version was designated the X-48C.

The program's goal was to explore the low-speed flight control characteristics of the concept in order to model the behavior of large transport or cargo aircraft. Engineers were intrigued by the design's potential to get up to 30% better fuel economy than traditional aircraft because of its unique shape. Following installation of test instrumentation, the second aircraft, X-48B blended wing-body had its first five test flights in early 2007. (X-48 flight test)

Both X-48B technology demonstrators were built by Cranfield Aerospace in the United Kingdom to Boeing's specifications. The subscale prototypes have a wingspan of 20.4 feet, with prominent vertical fins and rudders at the wingtips and elevons along the trailing edges of the wings. Three JetCats, small R/C aircraft turbojet engines providing a combined thrust of about 150 pounds, powered the 523-pound gross weight aircraft. The X-48B had an estimated top airspeed of 118 knots (135 mph), a maximum altitude of about 10,000 feet and a flight duration of about 40 minutes.

Primary changes to the *"C"* model from the *"B"* model transformed it into an airframe noise-shielding configuration. External modifications included relocating the wingtip winglets inboard next to the engine exhaust ducts, effectively turning the winglets into twin vertical tails. The aft deck of the aircraft was extended about two feet to the rear. Finally, the project team replaced the X-48B's three 50-pound thrust jet engines with two 89-pound thrust engines.

Time magazine's Nov. 12 edition highlighted the best inventions of the year for 2007. In the aircraft category, the magazine recognized the X-48B BWB for its innovative design and its potential to enable cleaner, quieter and higher performance air transportation.



X-48B in flight over Rogers Dry Lake. One of the lakebed runways is visible beneath the aircraft. This angle highlights the two engines in place of the original three, and the vertical fins helping to block engine noise. (NASA photo ED13-0056-02)

X-56

Armstrong continues developing high performance lightweight aircraft technologies. Lightweight wings, however, are more likely to experience aeroelastic phenomena such as flutter. The X-56A Multi Utility Technology Testbed (MUTT) first flew off of Rogers Dry Lake at Edwards AFB in July 2013. Starting in 2014, researchers at NASA Armstrong conducted the agency's first flight of the MUTT No. 2. The flight marked the beginning of a research effort designed to yield significant advances in aeroservoelastic technology using a low-cost, modular, remotely piloted aerial vehicle. Aeroservoelasticity involves the interaction of an airplane's automatic flight controls with the response of non-rigid structures to aerodynamic forces.

The X-56A

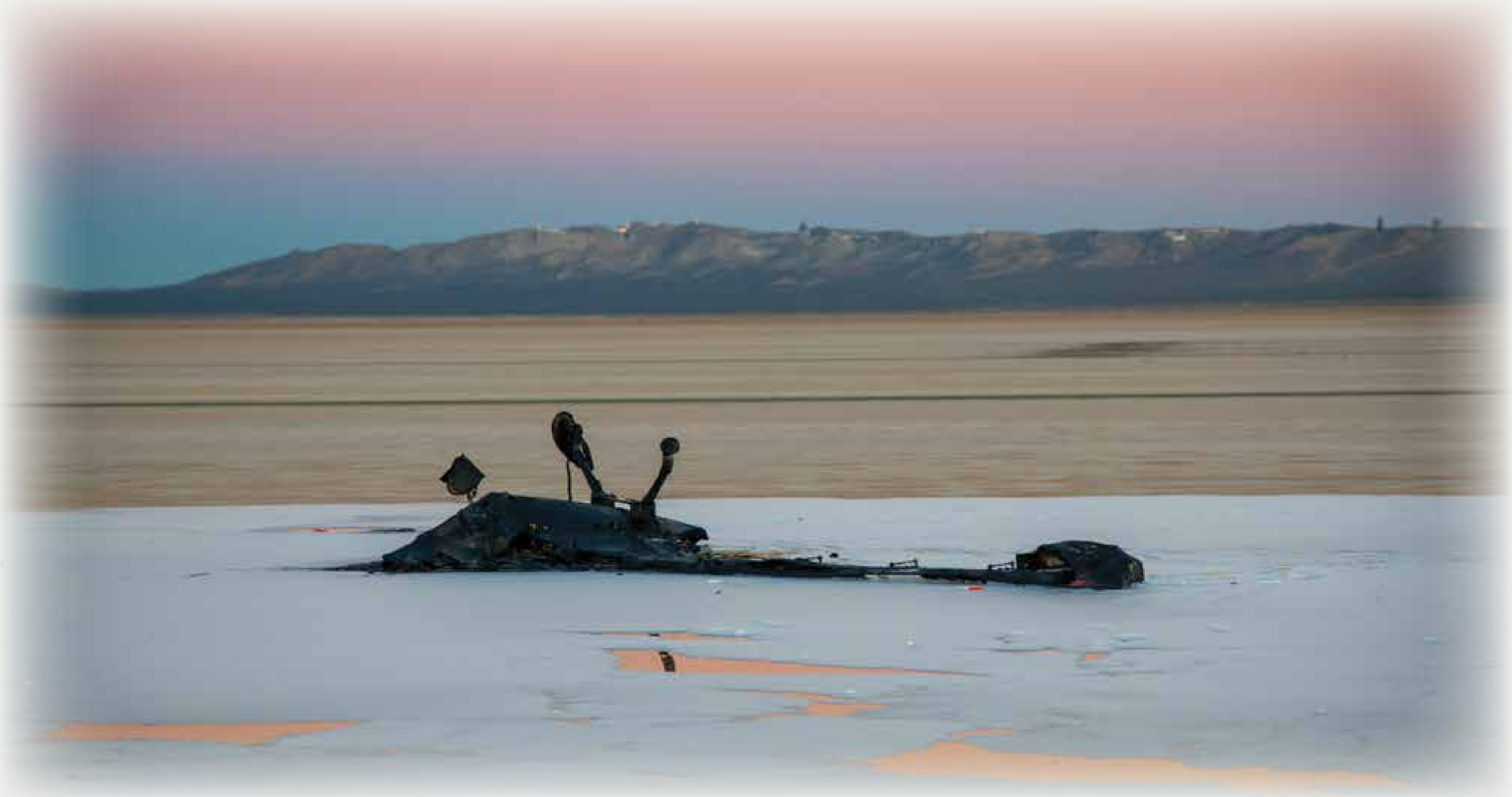
The X-56A was developed with exchangeable, lightweight wings to facilitate actively suppressing the vibrations with the control system. This research effort included a joint collaboration between Air Force Research Laboratory, Lockheed Martin Skunk Works and Armstrong. Lockheed Martin built two airframe center bodies along with several sets of wings because plans called for tests involving both stiff and flexible wings and there was the possibility that a wing might fail in flight (the center body carried a ballistic parachute for such an event). The maiden flight of the first airframe – nicknamed Fido – began exploring technologies for active flutter suppression and gust-load alleviation for new kinds of lightweight, flexible aircraft wings. The second airframe was dubbed Buckeye. (X-56A)

In December 2016, the X-56A aircraft and associated ground control system was transferred to Armstrong to continue flight research with the flexible wing set and NASA control laws. The team completed 48 research flights further developing aircraft models with validated flight test data. The control system was able to actively suppress flutter during these Phase 1 flights, with flights up to 10% beyond flutter speed.

In late 2019, X-56B (Buckeye) ventured into a new joint collaboration with AFRL and the Northrop Grumman Corporation to demonstrate the feasibility of active flutter suppression (AFS) and gust load alleviation through the use of an active, flexible motion control system. For the X-56B variant Northrop Grumman designed a wing set to attach to the X-56A center body along with the control laws.

The agency's effort includes participants from several NASA centers; engineers at Langley and Glenn are involved with modeling and analysis while Armstrong and AFRL are responsible for flight testing. Lockheed Martin also provided vital assistance and support. Researchers believe the next generation of aerospace vehicles will pose serious challenges to designers' ability to model, predict and control potentially destructive aeroservoelastic dynamics while trying to exploit efficiency gains from lighter, more flexible structures.

The first X-56A (Fido) was severely damaged in a crash after takeoff from Rogers Dry Lake in November 2015. The aircraft had previously made 16 flights with stiff wings to prove its operating envelope. The crash was attributed to interaction between landing gear dynamics and the flexible wings themselves, and this became its own subject of investigation. Fido's crash is indicative of the risks involved in flying experimental aircraft in uncharted territory; it's also a measure of the dangers to the center's research pilots when flying an aircraft from the cockpit – although in this case the pilot flew remotely – but it is the nature of the work the Amstrong performs. We often learn more from anomalies and failure than we do from success, as many have said, including Patrick Stoliker, center Deputy Director, and he's not the first to experience this firsthand.



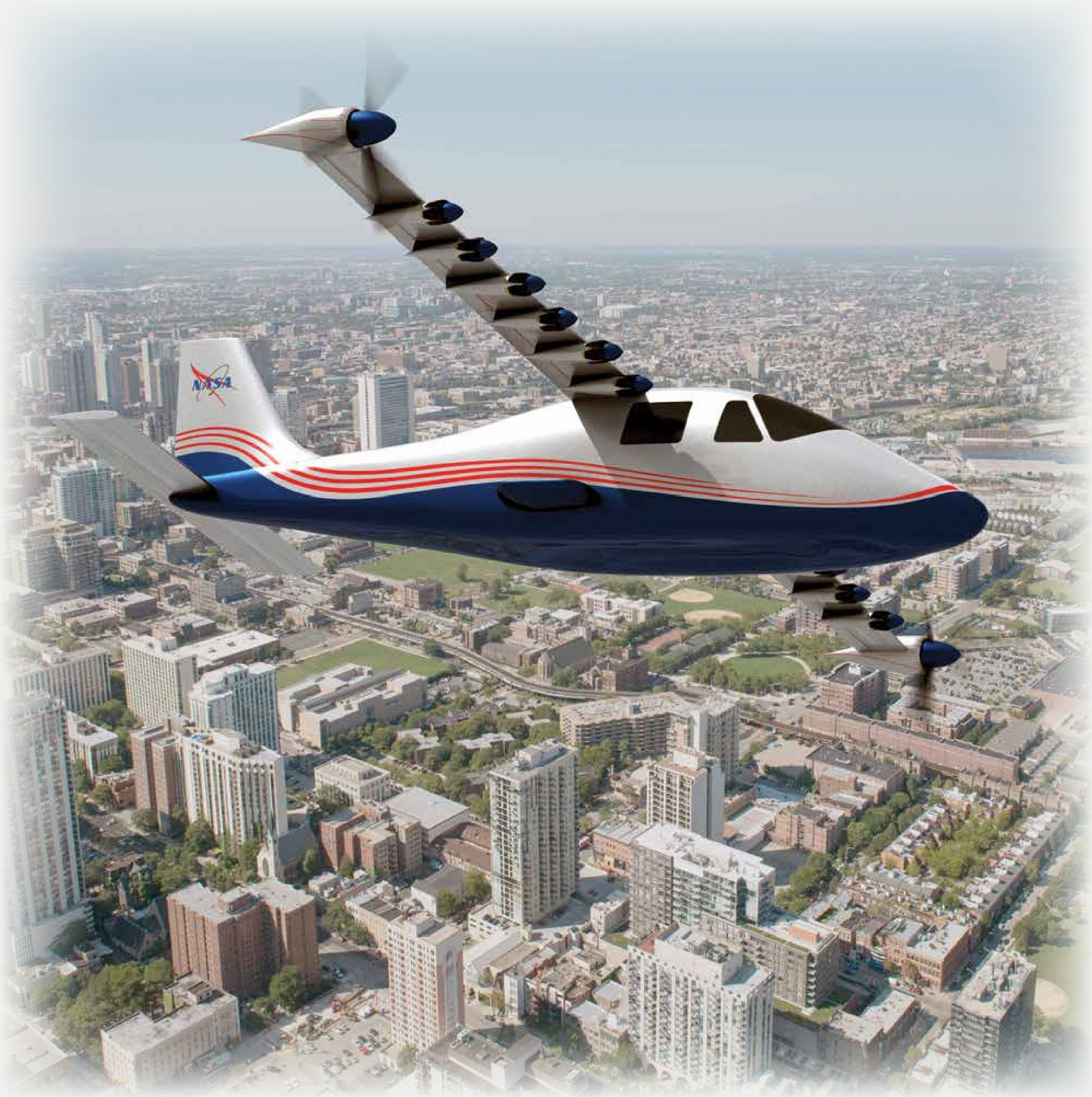
The X-56A lies on the lakebed following a landing accident involving the interaction of the aeroelastic wings and the landing gear. It came to rest on its back and burned. The aircraft lies in a puddle of fire suppressant foam. (NASA photo ED15-0355-043)

The second X-56A (Buckeye) flew for the first time in April 2015, making eight flights with the stiff wings to clear its operating envelope. The aircraft then made its first flight with the highly flexible wings in August 2017. In instability mode (body freedom flutter), the digital flight control system actively suppressed the flutter at 110 knots (200 kilometers per hour), within its normal flight envelope. The aircraft is remotely piloted from a ground control station. The X-56B flight test campaign will continue into 2021.

The X-57

NASA Armstrong, Langley, Glenn and Ames are working in conjunction with multiple industry contractors, including Empirical Systems Aerospace (ESAero) – the prime contractor – to modify and flight test an all-electric variant of a General Aviation (GA) aircraft, a Tecnam P2006T twin-engine four-seat general aviation aircraft given the designation X-57 *"Maxwell."* It is the agency's first all-electric experimental aircraft, or X-plane, and is NASA's first crewed X-plane in nearly two decades. The purpose of the X-57 project is to demonstrate the performance of a complex, integrated electric propulsion system through manned flight test, and collaborate with standards and certification agencies to develop a certification basis for electric aircraft. This effort will evaluate the challenges and opportunities associated with electric propulsion systems using a vehicle that is designed to demonstrate a 5-fold decrease in energy required per mile of high-speed cruise, zero in-flight carbon emissions, and flight that is much quieter for the community on the ground. Additional goals include the sharing of airworthiness processes to assist in the development of certification approaches and methods for distributed electric propulsion aircraft. The X-57 project is intended to help advance the nation's science and industrial base through communication of integration approaches, lessons learned and best practices. Maxwell is already a reference platform for integrated distributed electric propulsion systems. (X-57 overview)

The X-57 project is divided into four primary modifications. Each modification results in an incremental build-up in system complexity. Modification I (Mod I), now completed, began with the use of a Tecnam P2006T GA aircraft and involved collecting inflight data for the stock aircraft configuration. The Mod II configuration, currently underway, involves ground and flight testing of the primary electric propulsion system in the base GA aircraft. The Mod III configuration is being concurrently developed; it will demonstrate an experimental wing optimized for high-speed, efficient cruise flight with the primary electric motors installed in the wingtips. Mod IV adds low-speed performance with the addition of 12 smaller electric motors with folding propellers that will provide the benefits of high lift at low speed on the cruise-optimized Mod III wing. The Mod IV flight tests will demonstrate the benefits of distributed electric propulsion, which will revolutionize electric aircraft architecture and performance. Mod III and IV efforts were combined to accelerate development and discovery.



An artist's rendering of the X-57 in its final configuration: only the cruise engines are operating in this rendition. (NASA)

The X-59

The X-57, in its final form of the project, features 12 high-lift motors along the leading edge of the distributed electric propulsion wing.

The high-lift motors and propellers are designed to activate, along with the wingtip cruise motors, to get the X-plane airborne. When the plane levels out for cruise mode, the high-lift motors will then deactivate, and the five propeller blades for each motor will then stop rotating, then fold into the nacelles, so that they don't create unwanted drag during cruise. The two wingtip cruise motors will maintain flight during this phase of the flight.

When the time comes to land, the motors will then reactivate and centrifugal force will cause the propeller blades to unfold to create the appropriate lift for approach and landing.

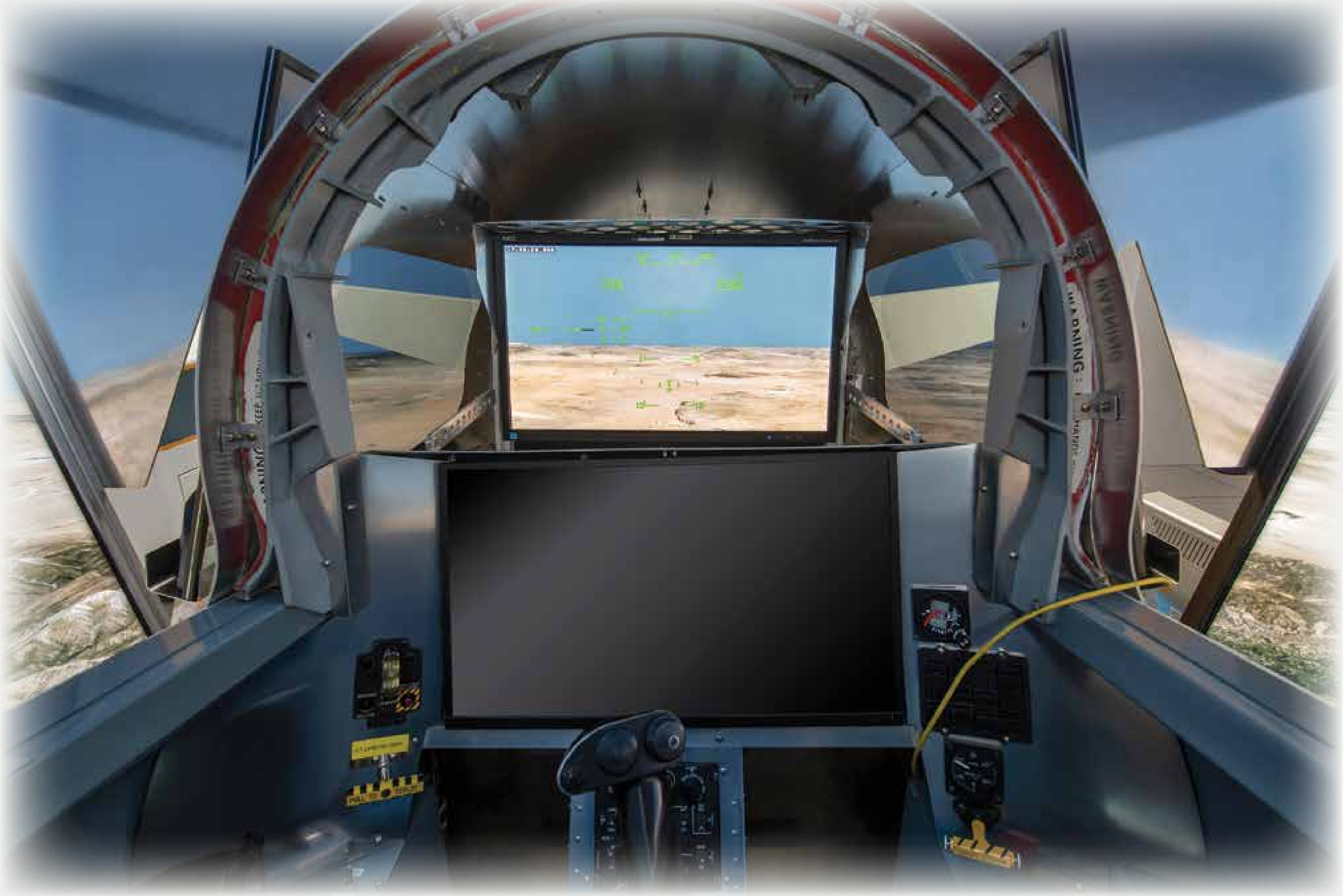
The design driver for X-57 will also seek to reach the goal of zero carbon emissions in flight, which would surpass the 2035 N+3 efficiency goals. Electric propulsion provides not only a five-to-ten times reduction in greenhouse gas emissions, but it also provides a technology path for aircraft to eliminate 100 low lead avgas, which is the leading contributor to current lead environmental emissions.

X-59 Low Boom Flight Demonstrator

The agency's most recent assault on the obstacle to commercial supersonic flight over land, the X-59 Low-Boom Flight Demonstration (LBFD), is a multi-center initiative. The X-59 is a follow-on to the F-5 Shaped Sonic Boom Demonstrator and the Grumman Corp/NASA F-15 telescoping nose boom called a *"quiet spike,"* as well as a number of other NASA supersonic boom reduction projects. The objective is to help the FAA and International Civil Aviation Organization (ICAO) establish new rules governing supersonic flight over land by developing an aircraft whose supersonic signature is below any existing supersonic aircraft—and a threshold the public will find acceptable.

"The project has a non-traditional organization: It is not based at any particular center but managed by NASA HQ. The project then draws the best expertise in the needed technical areas from the four aero centers," said Jay Brandon. All the NASA aeronautics centers are involved in the work, with Armstrong as the center that will flight test the aircraft, then conduct the overflight tests of different communities – with their knowledge and cooperation. Lockheed Martin won the contract to build the X-59 LBFD platform. (LBFD project)

As far back as the 1960s, the military, NASA and other research agencies began studies to gauge public response to supersonic traffic over urban areas. The results were not promising: The number of health and property damage complaints convinced the parties that supersonic overflights were intolerable because of the strength of the sonic boom. (Sonic booms)



A cockpit view (concept image) of the X-59 Low Boom Flight Demonstrator, highlighting the lack of forward visibility. The center screen is what the pilot will rely on in place of a windscreen – with the HUD overlaid on the screen. (NASA AFRC2019-0182-01)

The X-59

"The sonic boom continued to be an obstacle until computational fluid dynamics and test techniques improved to the point where designs could be developed that reduced the loud sonic booms," added Brandon. *"This was done by designing the airplane to prevent the myriad pressure variations from coalescing into single front and aft pressure peaks. Those rapid changes of pressure from the front and rear of the airplane cause the classic sonic boom 'double-clap' noise. By careful design, tailoring of the lift distribution and volume distribution of the airplane, the changes of pressure caused by the supersonic flight can be reduced, but more importantly, spread out across the length of the airplane, instead of coalescing just at the front and rear of the airplane."*

The X-59's role is to provide the data needed for regulatory change regarding civil supersonic flight over land. After a flight test program conducted at Armstrong, the X-59 program will send the aircraft and a team on the road, taking it to pre-selected cities for sonic boom tests. Once a community test site is selected, NASA will finalize the specifics to that test. For example, NASA will determine the appropriate supersonic cruise (ie., Mach = 1.4) flight track to enable test site measurements and community surveys within the desired sonic boom carpet and test conditions. *"NASA's current plan is to fly up to three flights per day (two exposures per flight) over a period of several weeks to collect the required community response data at each test site,"* said Dave Richwine, Deputy Program Manager, of Langley.

Because the aircraft will cruise above 50,000 feet altitude, the pilot will wear a partial pressure suit in the event of a cabin depressurization. Designing for a low sonic boom noise shape means eliminating the forward window on the aircraft. The solution: a *"virtual"* window using a very high resolution camera with onboard image processing and a high-resolution monitor mounted in the cockpit. While the shape of the aircraft is unique – it is very long compared to its wingspan – it *"borrows"* from existing aircraft to keep costs down, including an F-16 landing gear, a T-38 rear seat canopy, as well as components from F-18s, F-15s and F-16s. In that sense, it is a throw back to the X-29.

There are three phases to the project. Phase 1 is to develop the aircraft and expand the envelope so that the X-59 is safe to fly. (X-59 simulation) Phase 2 will include the partner teams –not only LBFD, but also the Commercial Supersonic Technology (CST) project. Phase 2 will see sonic boom noise validation and characterization and it is in this phase (done at Armstrong) NASA will validate the design tools for the quiet supersonic airplane. Phase 3, the *"operational"* phase, is the gathering of community responses to supersonic overflight. Armstrong hosts the major contracts (airframe with Lockheed Skunkworks and engines from GE).

Laminar Flow and DREs

NASA began a series of flights in 2017 to improve the efficiency of future supersonic aircraft following developments identified by high-speed wind tunnel testing conducted at Langley. As NASA developed the LBFD aircraft (X-59), the agency's CST project investigated ways to mitigate the disruptive sonic boom associated with supersonic flight, as well as approaches to other technical barriers to commercial supersonic flight. One barrier is fuel efficiency. At supersonic speeds, the drag that must be overcome is large: air flowing over a wing is slowed due to friction with the surface, creating drag that contributes about half of the aircraft's total drag at supersonic speeds. This particular series of flights explored ways of reducing friction drag and increasing efficiency on swept wing laminar flow.

As an aircraft flies, there is a very thin layer of air, the boundary layer develops between the surface of a wing and the free-stream air. This boundary layer generally begins as a smooth, or laminar flow, creating minimal friction drag. However, as air flow progresses over the aircraft's surfaces, tiny disturbances begin to affect the boundary layer and it eventually transitions into a turbulent flow, which produces much more drag. On swept wing aircraft, the aerodynamic challenge is overcoming crossflow on the wing when airflow runs along the span of the wing resulting in turbulent flow, increased drag and higher fuel consumption. Future supersonic aircraft seeking to achieve a low-boom, such as the X-59, rely on a swept wing to fly at supersonic speeds, but the swept wing design generally produces crossflow.

NASA believes this may be overcome by using an array of small dots, called distributed roughness elements, or DREs. *"Swept wings do not have much natural laminar flow at supersonic speeds, so in order to create a smoother flow over the wing, we're putting the DREs along the leading edge of the wing,"* says Armstrong CST subproject manager Brett Pauer. *"These DREs can create small disturbances that lead to a greater extent of laminar flow."* The DRE's work by modifying the crossflow growth within the boundary layer, delaying transition to turbulent flow.

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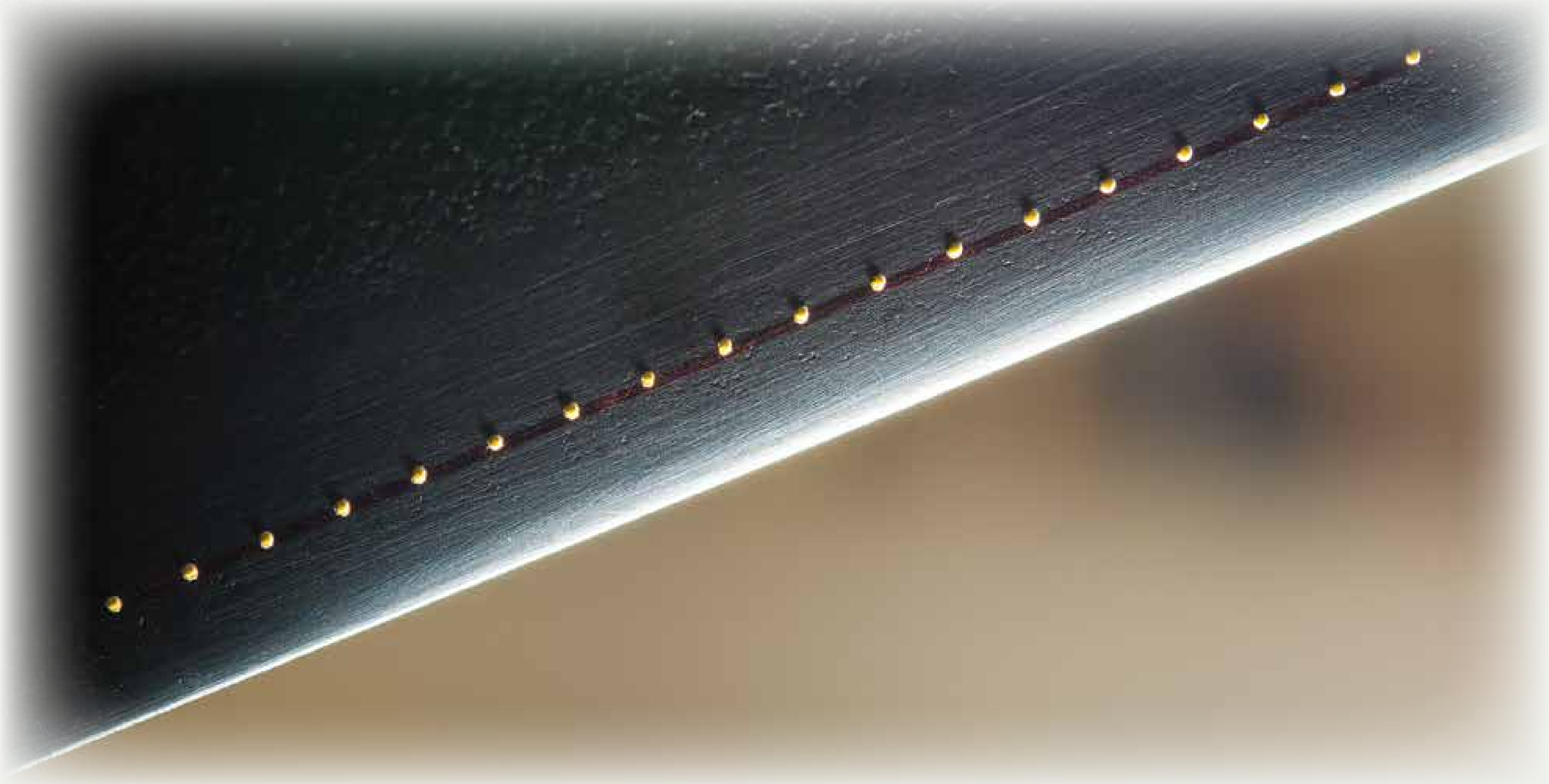
"We recently completed testing the 65-degree swept wing model at Langley," said Dan Banks, Armstrong principal investigator. *"Part of the purpose for the flight tests will be to document the differences in crossflow transition between that which occurs in the wind tunnel and that occurring in flight."*

The swept wing laminar flow efforts extend previous NASA research performed between 1988 and 1996 using two F-16XL aircraft. Those tests investigated the use of suction to maintain laminar flow using perforations in the porous titanium material on the wing. If successful, the DREs are a much simpler and more elegant solution. Swept wing laminar flow technology allows NASA to consider wing designs that have low boom characteristics but are more efficient. In the past, a large extent of laminar flow had only been practically achieved on wing designs with very little sweep. *"Supersonic laminar flow is an elusive holy grail for aerodynamicists,"* said CST project manager Peter Coen. *"This test, while still exploring fundamentals, is an important step toward achieving CST's fuel efficiency goals for quiet supersonic overland airliners."*



Distributed roughness elements, the small dots on the wing's leading edge, trip laminar flow, helping to keep airflow attached to the wing even at supersonic speeds. (NASA AFRC2019-0182-01)

Pad Abort 1

As part of the Constellation program and Orion crew exploration vehicle development, AFRC prepared the crew module for integration, then led the flight test vehicle integration for the Pad Abort 1 (PA-1), performed at the U.S. Army's White Sands Missile Range (WSMR) near Las Cruces, N.M. in 2010. The launch abort system (LAS), is designed to activate within milliseconds in an emergency on the launch pad or during initial ascent. When triggered, the abort motor fires to pull the crew module up and away from the launch vehicle; the attitude control motor exerts as much as 7,000 pounds of steering force to reorient the vehicle's position and the jettison motor separates the crew module from the launch abort system so that parachutes can be deployed for a safe landing.

In the 2010 test the 500,000-lb. thrust abort motor yanked the boilerplate crew module and its launch abort stack away from launch pad and all systems for steering, separation, stabilization, deployment of the parachutes and landing worked as designed. The Orion test capsule, suspended from its three red-and-white main chutes, landed about 6,900 feet downrange from the launch pad about 2½ minutes after the abort motors fired. AFRC sent a contingent of engineers to work at WSMR for the test, most of whom were on-site long term.

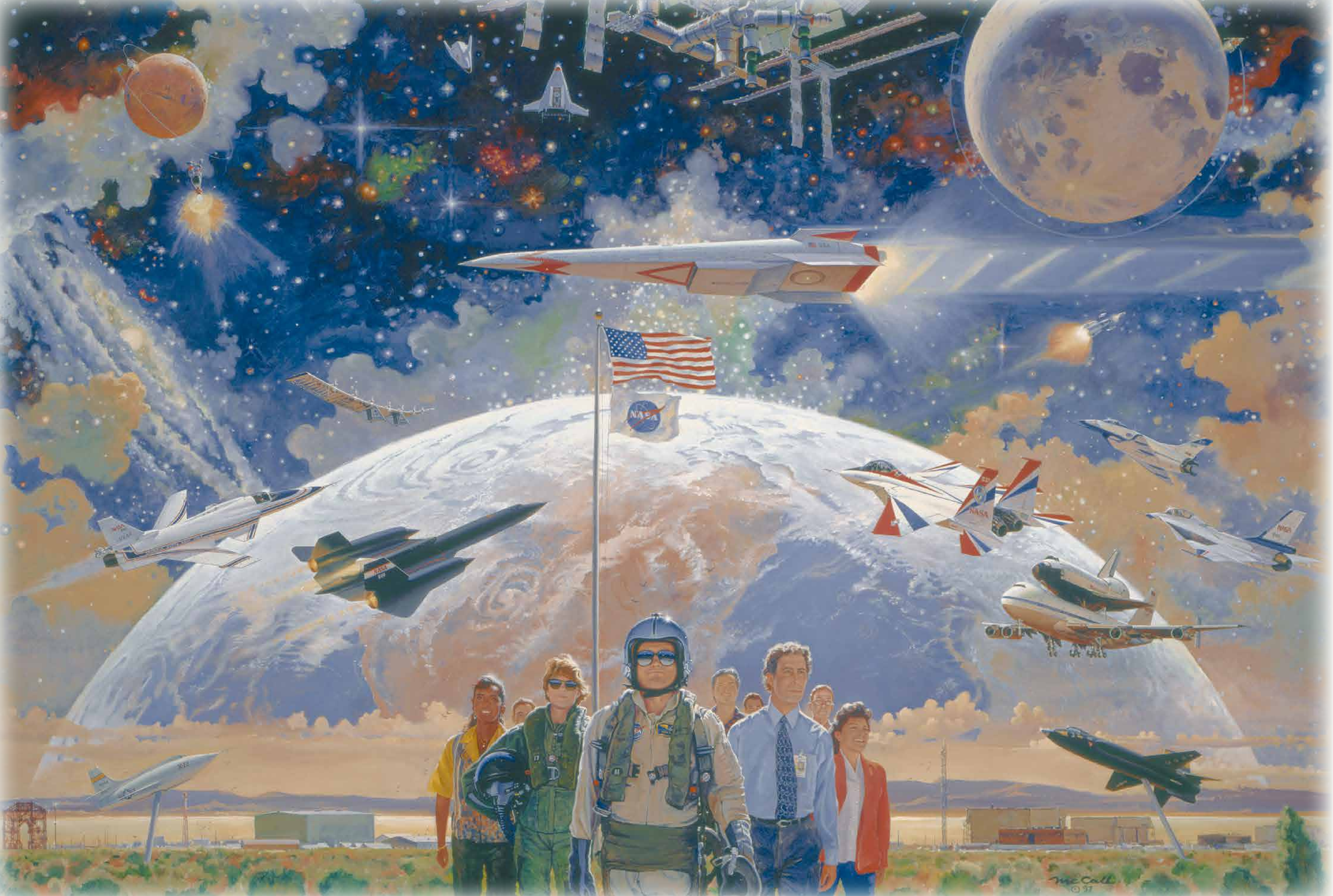
Conclusion

When the first 13 employees of the Langley Memorial Aeronautical Laboratory came to the High Desert and the dry lakebeds of the Mojave Desert in 1946, few, if any, of the engineers, pilots, computers and managers thought they would still have a presence here 75 years on. They arrived with one goal – support the X-1 in its pursuit of supersonic flight—after which they expected to go home. It was not to be. Even before the X-1 exceeded Mach, those from the NACA stationed at Muroc began to suspect their plans might change: the mounting evidence revealed how little they knew about transonic and supersonic flight in terms of materials, aerodynamics, propulsion, human physiology at high altitudes and more. What followed was a bittersweet epiphany: as the X-1 wound down they found a host of new questions to ask and answer, and this meant new and open-ended research; this also meant they would not be going back to the Tidewater region any time soon.

Conclusion

Seventy-five years later the Armstrong Flight Research Center remains engaged in even broader exploration than the first group enjoyed. Aeronautics remains a major component of the center's mission, as it had from the beginning. Access to space entered the Center's portfolio in the mid-1950s (reaction control systems thrusters for the X-15) and it has remained a vibrant aspect of Armstrong's work (Flight Opportunities, Dream Chaser, support for JPL's Mars Rovers, TGALS and more). Airborne Science became another page in the portfolio of work. To this NASA added sustained, quiet supersonic flight, remotely piloted aircraft, structural research and health management of aircraft (FOSS) and such avant garde projects as Fused Reality, PRANDTL-D and DRE. And after a hiatus of nearly 15 years, X-planes have returned to the center – four at once! These projects of national significance run the gamut from slow speed to supersonic flight, from remotely piloted aircraft to an all-electric aircraft research test bed. The Center's workforce is professionally diverse (at about 1,150 employees, split almost evenly between contractor and civil servant), with engineers, pilots and mechanics, to structural engineers, EEs, computer programmers, accountants, systems managers, photographers and videographers, research librarians, flight related medical staff, public affairs officers and many other categories of full-time employment, including one historian.

The center is a hub of intellectual activity, the products of which benefit the nation and humanity.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Accepting the Challenge of Flight

by Robert McCall

A New Name